MONTHLY NOTICES

OF THE

ROYAL ASTRONOMICAL SOCIETY

CONTAINING

PAPERS, ABSTRACTS OF PAPERS, AND REPORTS
OF THE PROCEEDINGS OF THE SOCIETY

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Professor H. H. Plaskett, M.A., F.R.S.,
President, 1945-47

MONTHLY NOTICES

OF THE

ROYAL ASTRONOMICAL SOCIETY

Vol. 107 No. 1

MEETING OF 1947 JANUARY 10

Professor H. H. Plaskett, President, in the Chair

The election by the Council of the following Fellows was duly confirmed :—

Charles Gordon Abel, 8 Tankridge Road, Cricklewood, London, N.W. 2;

Angus Armitage, 52 Parkhill Road, London, N.W. 3;

Hugh Townshend Vesey Church, Redroof, Felpham, Bognor Regis, Sussex;

Kenneth Roy Coleman, B.Sc., 78 Sheaf Lane, Sheldon, Birmingham, 26;

Hugh Roland Cooper, The Port Office, Saldanha, Cape Province, S. Africa;

Cyril Tetlow Daltry, B.Sc., 99 Maze Hill, Greenwich, London, S.E. 10;

William Henry Douglas Heavens, Boars Hill, Oxford;

Albert Francis Arthur Lofley Jones, 40 Trafalgar Street, Timaru, New Zealand;

Sir Philip Magnus, Bart., B.A., The Athenaeum Club, Pall Mall, London, S.W. 1;

Graham James Odgers, Solar Physics Observatory, Cambridge;

Alan Bernard Partridge, B.A., Peterhouse, Cambridge;

Edward H. Preston, Hayden Planetarium, American Museum of Natural History, Central Park West at 79th Street, New York 24, U.S.A.;

William Edward Reynolds, Brockley, Netherfield Drive, Guiseley, near Leeds, Yorkshire;

Herbert Edgar Sweet, Brix, 21 Rutland Road, Maidenhead, Berkshire;

Frederick Edward Townend, M.B.E., 39 Park Avenue, Grimsby, Lincolnshire;

Brian Gilbert Wales-Smith, 1 Mount Park Crescent, Ealing, London, W. 5; and

George Gilbert Yates, M.A., Solar Physics Observatory, Cambridge.

The following candidates were proposed for election as Fellows of the Society, the names of the proposers from personal knowledge being appended :—

Ian Douglas Anderson, Almora, Laura Grove, Paignton, Devon (proposed by V. Barocas);

James Stanley Hey, Broad Oaks, West Byfleet, Surrey (proposed by A. Hunter);

Kenneth Frank Stonebridge, 61 Crowshott Avenue, Stanmore, Middlesex (proposed by J. H. J. Burtt);

Rev Patrick Joseph Treanor, S.J., B.A., University Observatory, Oxford (proposed by H. H. Plaskett); and

Charles Garrie Wynne, B.A., 52 London Lane, Bromley, Kent (proposed by E. H. Linfoot).

Fifty-seven presents were announced as having been received since the last ordinary meeting, including :—

A. S. Eddington, *Fundamental Theory* (presented by Mr R. H. Garstang).

The President announced that the Council had awarded the Gold Medal of the Society to Professor Marcel Gilles Jozef Minnaert, of the University of Utrecht, for his outstanding contribution to solar physics in general and spectrophotometry in particular.

The President further announced that the Council, with the approval of the donor, had decided to offer for sale to Fellows certain of the books and instruments presented to the Society by the daughter of the late A. C. Allen.

ANNIVERSARY MEETING OF 1947 FEBRUARY 14

Professor H. H. Plaskett, President, in the Chair

The election by the Council of the following Fellows was duly confirmed :—

Arthur Francis O'Donel Alexander, M.A., Ph.D., Cartref, 1 Athelstan Road, Dorchester;

David Robert Bates, M.Sc., Lecturer in Mathematics, University College, Gower Street, London, W.C. 1;

Pedro Marcos Bilbao, 10 The Grange, Maitland Park Road, London, N.W. 3;

Sydney Goodchild, 1st Bn. Sikh Light Infantry, Poona, India;

Neville James Goodman, Fosswyn, Luton Road, Markyate, Hertfordshire;

Henry Howard Hammond, M.B.E., 26 Southdean Gardens, Wimbledon Park, London, S.W. 19;

Maurice Neville Hill, B.A., King's College, Cambridge;

Kurt August Hirsch, Ph.D., D.Phil., 22 Northcote Road, Leicester;

Rev. Horace Charles Colin Hunt, 5 Stoke Road, Aylesbury, Buckinghamshire;

Henry Ernest Ruddy, M.A., Braunston Rectory, Rugby, Warwickshire;

John Herbert Jennings Westlake, The Cedars, Victoria Road, Deal, Kent; and

Patrick Lever Willmore, B.A., St. John's College, Cambridge.

The following candidates were proposed for election as Fellows of the Society, the names of the proposers from personal knowledge being appended :—

Wilfred John Bates, Wills Hall, Stoke Bishop, Bristol, 9 (proposed by C. R. Burch);

David William Dewhirst, Christ's College, Cambridge (proposed by H. A. Brück);

Kenneth R. Eldredge, 20 Grosvenor Square, London, W. 1 (proposed by J. R. Pikett);

Rómulo Grandón, Casilla 88, San Bernardo, Chile (proposed by F. Rutllant);

Axel Nicolai Herlofson, University Observatory, Oxford (proposed by S. Chapman);

Constantine J. Tenukest, 69 High Street, Willoughby, New South Wales, Australia (proposed by H. Wood); and

Rupert Wildt, Yale University Observatory, Prospect and Canner Streets, New Haven 11, Connecticut, U.S.A. (proposed by S. Chandrasekhar).

Sixty-five presents were announced as having been received since the last meeting.

The President announced that Professor M. G. J. Minnaert, Gold Medallist for 1947, would deliver the George Darwin Lecture at the Ordinary Meeting on 1947 May 9, the provisional title being : " The Fraunhofer Lines in the Sun ".

The President then delivered his address on " Astronomical Spectroscopy ".

1947 FEBRUARY 14

ANNUAL GENERAL MEETING

Professor H. H. Plaskett, President, in the Chair

The Minutes of the preceding Annual General Meeting were read, confirmed and signed.

The President having appointed the Scrutineers, the Society proceeded to the ballot for Officers and Council for the ensuing year.

The Secretary read extracts from the Narrative Report of the Council.

The Report of the Honorary Auditors was read (see p. 20).

The Secretary, in the absence of the Treasurer abroad, remarked on a few items in the Accounts relative to the financial state of the Society.

A vote of thanks to the Honorary Auditors of the Treasurer's Accounts for 1946 was proposed and carried unanimously.

It was proposed and carried that the Report of the Council be received and adopted, and that it be printed and circulated in the usual manner, together with the Report of the Honorary Auditors and the President's Address.

The Secretaries, on behalf of the Council, moved the adoption of the amended Bye-law 22 below, which was put to the Meeting, and after some further explanation from the Secretaries, adopted unanimously :—

> 22. The contribution of each Fellow shall, for the first year, be five guineas, or three guineas, according to the month in which he may have been elected (viz. two guineas in all cases as an admission fee, and three guineas as the first year's contribution, if such election has taken place in the month of January, February, March, April, May or June ; but only one guinea as the first year's contribution if such election has taken place in the month of October, November or December), payable at the time of his election ; and three guineas for every subsequent year ; the first of such subsequent contributions to become due and be payable in advance on the 1st day of January in every subsequent year.

The Scrutineers reported to the President the result of the ballot, and the names of the Officers and Council elected for the ensuing year were read to the Meeting. (The list of names is given on p. 151.)

The newly elected President (Professor W. M. H. Greaves) and the Secretaries (Professor W. H. McCrea and Dr A. D. Thackeray) then took their places.

The thanks of the Society were given to the retiring President (Professor H. H. Plaskett), Vice-Presidents (Dr H. R. Hulme, Professor E. A. Milne), Vice-President and Deputy Treasurer (Mr J. H. Reynolds), Secretary (Mr D. H. Sadler) and other retiring Members of the Council.

The thanks of the Meeting were given to the Scrutineers of the ballot.

The Meeting then adjourned.

REPORT OF THE COUNCIL TO THE HUNDRED AND TWENTY-SEVENTH ANNUAL GENERAL MEETING OF THE SOCIETY

1. *General.*—In any astronomical review of the events of the year 1946, pride of place must be given to the announcement on July 15 by Sir Robert Robinson, President of the Royal Society, that the Chancellor of the Exchequer had agreed to ask Parliament to vote a sum of money adequate to build an observatory, to be known as The Isaac Newton Observatory, equipped with a 100-inch telescope (The Isaac Newton Telescope) and its necessary ancillary equipment. This, in the words of the President, " the greatest single contribution to the development of observational astronomy in this country ", has illumined the whole future of British astronomy and has brought to the Society an added stimulus rapidly to overcome the lingering aftermath of six years of war. The part played by the Society in this triumphant achievement has been described in detail in an article in *The Observatory* for December 1946, which all Fellows will have received; as promised in that article the full texts of the two memoranda submitted by the Society to the President and Council of the Royal Society are now published by permission of the Royal Society as an appendix to this Report. It is still too early to give an account of the organization to be adopted for the Observatory, but it may be assumed that the proposals made by the Society will be accepted in broad outline.

As anticipated in last year's Report the return to the full exercise of pre-war activities of the Society has been slow, especially in regard to those making demands on industrial resources. The Society has been particularly unfortunate in this respect in regard to the printing of its publications and the Council asks the indulgence of authors and Fellows for the long delays that have occurred in publication. The difficulty is common to all scientific societies to a greater or smaller degree, and the Council has, in addition to making new arrangements for printing, raised the whole question of the inadequacy of the provision for mathematical composition for discussion centrally at a high level. It will also be seen from the detailed Report that follows that the Council has not been able to carry out its reconstruction plans in regard to the restocking of slides and prints, the binding of books in the Library and in other spheres.

On the other hand the meetings of the Society—and during the year there have been, including Geophysical Discussions and the evening meeting or Conversazione, a record number of 15—can rarely have attained such a consistent measure of interest, support and enthusiasm. Although relatively few Fellows are able regularly to attend meetings of the Society, they are the very essence of a corporate body and it is the Council's earnest endeavour to encourage Fellows to attend whenever possible. Successful scientific meetings however, require the inspiration and the spirit of original work, and it is gratifying to record that the number of scientific papers received, although not yet up to pre-war average, shows a continuing increase; the small number of authors from this country is clear evidence of the dearth of the younger research astronomers, from whom the majority of papers would be expected. It is to be hoped that the gap caused by the

almost complete cessation of recruitment and training during the war will be rapidly closed, now that astronomers will have in the future the incentive of access to the finest observational equipment which the climate of this country will allow.

Administratively, the year has been the busiest for a long time and the Council has recognized the particularly heavy burdens carried by the Assistant Secretary, Miss Wadsworth, by an increase in her salary and the appointment of an Assistant, intended to succeed in due course to the post of Assistant Secretary, but appointed now to help with the extra work arising from the full resumption of activities and the making up of war-time arrears.

This appointment, so necessary for the efficient working of the Office, has added temporarily at least, to the general increase in salaries and wages; taken together with the 70 per cent increase in the cost of printing this has meant that the Society's expenditure under both the principal headings of salaries and printing, has almost doubled, without any significant increase in income. Owing to war-time curtailment of activities and staff, the Society was able to put money aside during the war years, but the major portion of the unfavourable balance is likely to be of a permanent nature; the Council has therefore reluctantly decided to ask the Annual General Meeting to approve an increase in the Annual Contribution, to operate as from 1948 January 1. The price of the Society's publications to outside subscribers will be increased as from 1947 January 1.

This Report of the Council follows the new standardized form, with one modification. The Council has decided that Obituary Notices shall not in future be given for all deceased Fellows, but only for those who had made some significant contribution to Astronomy. Proceedings of Observatories and Notes on the Progress of Astronomy are included in the usual manner.

2. *Bye-laws.*—At the Annual General Meeting on February 8 the Secretaries proposed, on behalf of the Council, a number of amendments to the existing Bye-laws; these were adopted unanimously by the Fellows. The majority of the alterations were of a minor character, mainly arising through slight inconsistencies between the existing Bye-laws and current practice.

One important alteration in principle was incorporated, namely the new Bye-law 48, which prohibits the Council from bringing forward at the Annual General Meeting business of which prior notice has not been given to Fellows. Although the freedom to do this had been invoked on one occasion during the war, the Council generally agreed that it should propose a limitation of its own powers to bring the Bye-laws into concert with democratic principles.

The amendments that will affect Fellows most directly are those concerned with the dates and times of ordinary meetings. In its detailed consideration of these questions the Council was assisted and guided by the wishes of Fellows as expressed in the postal ballot. The significant changes are the substitution of October for June as a month for a regular meeting and the beginning of meetings at $16^h\ 30^m$ instead of $17^h\ 00^m$. A relatively minor change, but one which has clarified certain anomalies in the Bye-laws and allowed of a more clear-cut agenda for the Annual General Meeting, is the rewording of Bye-law 46 to separate the Annual General Meeting from the preceding ordinary meeting in February (Anniversary Meeting) at which the President delivers his Address.

During the year a new edition of the Bye-laws, incorporating these changes and including dates of adoption and amendment, has been prepared; it should be printed and circulated to Fellows early in 1947.

3. *Membership.*—The Council records with regret the death of three Associates (Shin Hirayama, who was also a Fellow, Hisashi Kimura (1943) and George Willis Ritchey (1945)) and twenty-two Fellows; their deaths occured in 1946 except where an earlier year is indicated.

*Charles Edward Adams (1945)
*Charles Frederick Butterworth
Charles Stuart Cushing
George William Evans-Cross
Charles Andrew Fountaine
*Gustavo de Heredia
Kiyotsugu Hirayama (1943)
Kenneth Davies Hopkins (1942)
William Malin Hunt (1945)
*James Hopwood Jeans
Stanilas Kalinowski
Shunichi Kawasaki (1943)
Lionel William Pelling Lewis (1945)
Adrian van Maanen
*John Willoughby Meares
*Henry Crozier Plummer
Richard John Porter (1945)
*John James Steward
*James Watt (1945)
Violet Florence White
Jan Woltjer
Harry Edwin Wood

*Life Fellow.

Obituary Notices of the Associates and some of the above Fellows are given on pages 36-61.

A table giving detailed statistics of the Membership of the Society on 1947 January 1 is given on page 21. It is encouraging to note that the increased number of elections last year has been maintained.

4. *Finance.*—The Annual Accounts from 1946 January 1 to December 31 have been presented in a slightly modified form; they have been audited by the professional auditors, Messrs Sharp, Parsons & Co., and certified correct.

A grant of £500 was received through the Royal Society, from the Government Grant-in-Aid of Scientific Publications, towards the cost of printing the war-time arrears of *Monthly Notices* and *Geophysical Supplement.*

The Cash Account shows a cash balance at the Westminster Bank, Post Office Savings Bank and in the London Savings Bank on 1946 December 31 of £7574, 2s. 10d. as compared with £6321, 5s. 1d. on 1944 January 1.

The Revenue Account shows a net deficit of £540, 18s. 11d., after making the annual reserve for repairs of £40, adding £50 to the reserve for binding war-time periodicals and setting aside £100 for the Staff Pension Fund. The sum of £27 received from the sale of a set of Franklin-Adams Charts has been added to the reserve for the replacement of photographic slides and prints. Provision has had to be made, in adjusting reserves for printing, for the cost of printing the large number of papers which have accumulated as a consequence of printing delays. Increases in staff salaries and in printing charges are mainly responsible for the considerable deficit for the year.

The total of the Suspense Account, which includes unpaid Contributions and Admission Fees, has been reduced to £732, 18s. 0d. No credit for this sum has been taken in the Annual Accounts. The number of non-active Fellows has been substantially reduced during the year.

5. *Meetings during* 1946.—The Annual General Meeting was held, for the first time since 1939, in the traditional month of February; the new arrangement of separating it completely from the preceding Anniversary Meeting (see under *Bye-laws*) proved most satisfactory. There were in addition seven ordinary meetings in March, April, May, June, October, November and December. In honour of several French astronomers visiting this country an additional meeting was held in January, at which they gave accounts of the astronomical work on which they had been engaged during the war.

The George Darwin Lecture was delivered at the May meeting and at the June meeting a " Discussion on the Use of a Large Telescope in Britain " was organized in support of the Society's application to the Royal Society (see page 4) ; the remaining meetings were devoted to the reading of original papers communicated to the Society, culminating in a well attended discussion at the December meeting based on three papers on the observation of meteors by visual, radio and radar methods.

The average attendance of Fellows (as shown by the signatures in the Attendance Book, and excluding visitors) was 67 as compared with 56 in 1945; this increase is most welcome and it is hoped that meetings will continue to attract such audiences.

The change over from the war-time arrangements for meetings has now been completed and they are now arranged in accordance with the revised Bye-laws. It is notable that in the first year of their operation, appeal was necessary to the permissive footnote allowing a meeting in June.

6. *Geophysical Discussions.*—A full programme of five Geophysical Discussions was held during the year, the dates and subjects being :—

February	22	Clouds
April	26	Tropical Meteorology
May	31	The Ionosphere
October	25	The Burton-on-Trent Explosion
November	22	English Oilfields

The Council is most grateful to those, Fellows and others, who contribute to these successful discussions.

7. *Celebrations.*—A conversazione to celebrate the centenary of the " Discovery of Neptune ", and to commemorate the quatercentenary and tercentenary of the births of Tycho Brahe and Flamsteed, was held in the Society's rooms on October 8. During the evening Professor W. M. Smart delivered two addresses on " J. C. Adams and the Discovery of Neptune ". The full text of this address, containing much unpublished biographical material, will be published in due course as an *Occasional Note*. Exhibits relating to all three centenaries were on view in the Library while refreshments were served in the Upper Library.

The Council would like to take this opportunity of thanking Professor Smart and all those who lent exhibits or contributed to the organization of the conversazione for their share in a most successful evening.

8. *George Darwin Lecture.*—Professor Jan Hendrik Oort, Director of the Leiden Observatory, Holland, gave the George Darwin Lecture at the ordinary meeting on May 10, the subject being " Some phenomena connected with interstellar matter ". This address is printed in *Monthly Notices*, Vol. **106**, No. 3.

9. *Awards and Elections.*—The Council awarded the Gold Medal of the Society to Professor Jan Hendrik Oort for his investigations on the dynamics and rotation of the galactic system. It was presented to him on the occasion of his giving the George Darwin Lecture: and the President's address on the presentation is included in the report of the May meeting.

The Council awarded a Jackson-Gwilt Medal and Gift, in accordance with the terms of the award, to Mr Harold William Newton of the Royal Observatory, Greenwich, for his work on the Sun, notably on the relation between solar flares and magnetic storms. The President's address on the award is printed in the report of the Anniversary Meeting, *Monthly Notices*, Vol. **106**, No. 2.

Professor Thaddaus Banachiewicz, Professor Ira Sprague Bowen, Dr André Joseph Alexandre Couder, Professor André Danjon, Dr Eugène Delporte were elected Associates of the Society.

10. *Publications and Printing.*—During the year 1946 the Society has published only *Monthly Notices*, Vol. **106**, No. 1, though Nos. 5 and 6 of Vol. **105** were actually distributed, and Nos. 2 and 3 of Vol. **106** are in the press. No *Occasional Notes*, no *Geophysical Supplements* and no *List of Fellows* has been published, although the translation of the Preface and Book I of *De Revolutionibus* by Copernicus is now in proof, and a new list of Fellows is in active preparation.

The Council expresses its regret to Fellows for the printing delays which have so seriously interfered with the regular appearance of *Monthly Notices* and have jeopardized the Society's reputation for speedy publication. After preliminary tentative enquiries for another suitable printer in the early part of the year, it later became clear that a change of printer was essential. The Society has been fortunate in securing the services of the old-established firm of Messrs Taylor & Francis Ltd., who have taken over the Society's printing from *Monthly Notices*, Vol. **106**, No. 3 onwards; and it is anticipated that most of the arrears will have been made up by the end of 1947. Fellows must realize that conditions in the printing industry are still very difficult and that a return to pre-war schedules is, as yet, out of the question.

In order to conform with the mathematical types which the new printer possesses it has been agreed to return to the larger type (11-point) used in the Society's pre-war publications; the mixture of types in Vol. **106** which is thus unavoidable is to be regretted. The present style adopted for Vol. **107** is a combination of the two, which it is hoped will appeal to Fellows. The larger type-area now used is, however, being retained.

The Council has decided to continue to restrict *Monthly Notices* to six numbers a year for both 1946 and 1947, but no schedule of publication dates is as yet possible.

11. *Exchange of Publications.*—During the year the Council has been able to arrange for the distribution of war-time numbers of *Monthly Notices* and *Geophysical Supplements* to all institutions on the Exchange List other than those in ex-enemy countries; some sets have been sent to these countries, but complete distribution is not yet possible. Current issues are being sent by ordinary postal channels or, in a few cases, by special arrangements, to all on the Exchange List, and to many observatories and institutions, which although not on the Exchange List are not in a position to remit payment. It is the Council's policy to ensure that astronomers everywhere have access to the Society's publications, though it is being made clear that free supply in present conditions does not commit the Society to placing an institution on the permanent Exchange List; the long over-due revision of this list, which has again been omitted from the Report,

is still postponed pending a more stable settlement of world conditions and communications.

The war-time gaps in the Society's copies of foreign publications are now mainly made up, with the exception of German periodicals, the stocks of which were either dispersed or destroyed. Efforts, through various channels, have been made to obtain copies of the missing numbers—but so far without complete success.

12. *The Library.*—The use made of the Library has shown a slight increase during the year; in 1946 430 books were borrowed by 117 different borrowers, as compared with the figures of 370 books and 96 different borrowers in the previous year. Visits to the Library for consultation now amount to about 130 a month.

No list of *Additions to the Library* (other than by exchange) was issued during 1946, though one covering additions to the end of 1945 was circulated with *Monthly Notices*, Vol. **105**, No. 5. During the year, the A. C. Allen books presented to the Society by his daughter were received and carefully sorted by the Library Committee. A number of the duplicate books are being disposed of (with the consent of the donor) in various ways, and some are being offered on sale to Fellows.

In view of the increasing demands on shelf space in the Library and the knowledge that any possible increase will only provide relief from congestion for a short period of years, the Council seriously considered the desirability of dispensing with or cutting up the Proceedings of certain Academies which now occupy a considerable proportion of this Library. It finally accepted the report of the Library Committee that the purely temporary advantage to be gained is insufficient to justify the permanent and possibly very great loss that would be entailed.

For still another year no binding has been done although arrangements have now been made for the arrears to be put in hand; funds are available for this purpose, though the cost of binding is now very high.

No progress has been made with the re-arrangement and re-cataloguing of the Library, and, in fact, much of the cataloguing of additions during the war years still remains to be done. With the increase in the Society's staff, it is now anticipated that a start will shortly be made on this much needed reform.

13. *The Society's Office and Staff.*—From the many replies to the Society's advertisements for an Assistant in the Office, with a view to succeeding to the post of Assistant Secretary on the retirement of the present holder, the Officers selected Miss M. F. M. Garratt, B.Sc., lately Assistant Secretary to the Society of Glass Technology, who commenced her new duties in November. Mrs U. M. Dewey, who has given exceedingly useful part-time assistance during a difficult period, left at the end of November after an overlap of a month with Miss Garratt.

It is anticipated that the addition of a full-time Assistant will provide some measure of relief for the Assistant Secretary, Miss E. Wadsworth, and will enable some of the arrears, which accumulated during the war years when the Office was under-staffed, particularly in regard to the Library, to be caught up.

During the year, the Outer Office formerly used mainly as a cloak-room has been refurnished and partly redecorated as an office proper. Fellows visiting the Society's rooms cannot but have been impressed by the great improvement in appearance thus effected.

14. *The Society's Premises, Property and Instruments.*—In addition to the alterations to the Outer Office, new radiators have been installed in the Hall and Main Library and a number of the benches in the Meeting Room have been recovered and repaired.

A few minor changes only have been made in the disposition of the Society's instruments and the Society still pays rent and upkeep for the instruments housed at the Headley Observatory. The revised list of instruments is still in preparation.

Strenuous efforts have been made to find suitable firms able and willing to make slides and prints up to the Society's standard; although two firms are being employed to make slides from the Society's negatives, the stock of slides is still small. A greater flow of work is hoped for as conditions gradually become easier.

15. " *The Observatory* ".—In accordance with the agreement of 1941 as subsequently renewed, Fellows have received the six 1946 issues of the magazine.

During the course of the year the Editors represented to the Council that, in spite of the greatly increased costs of production, they had increased the number of pages in the magazine almost to its pre-war figure and would have to increase the price to outside subscribers. The Council has accordingly agreed to an increased block subscription, varying with (but not proportional to) the price to outside subscribers.

16. *Guest Societies.*—

(*a*) *The British Astronomical Association.* During 1946 the British Astronomical Association continued to hold both Ordinary and Council Meetings in the Society's premises. The Association's Library is open to members from 13^h to 16^h on Wednesdays.

As a result of the automatic termination of the former agreement a new agreement has been entered into in the first place for a period of five years, but subject to renewal by mutual agreement. The new agreement allows for the more frequent use of the Association's Library, as soon as conditions permit.

(*b*) *The London Mathematical Society.* The regular programme of meetings was resumed and eight meetings were held in the Society's rooms.

(*c*) Office accommodation was made available for the use of delegates during the Empire Scientific Conference and the International Council of Scientific Unions.

THE ISAAC NEWTON OBSERVATORY: MEMORANDA ADDRESSED TO THE PRESIDENT AND COUNCIL OF THE ROYAL SOCIETY

First Memorandum, 1946 *May* 14.

The Council of the Royal Astronomical Society makes application for a sum of the order of £100,000 to build a reflecting telescope of at least 72 inches aperture, together with its dome, for observational astronomy in the United Kingdom. It proposes that this instrument should be erected at Herstmonceux, the new site of the Royal Observatory, and should be under the administrative direction of the Astronomer Royal; it proposes that the observing programme should be drawn up by a Board of Management in such a way as to ensure equal opportunities for the use of the telescope to the astronomers of all the observatories in the country. In view of the forthcoming commemoration of the tercentenary of the birth of Newton and in view of the fact that the first reflecting telescope was made by him, the Society (following a suggestion of Professor S. Chapman) proposes that the instrument with its building be known as the Isaac Newton Observatory.

The Need for a Large Telescope in Britain.—Successful research in many branches of stellar astronomy to-day is only possible with a telescope of large light-gathering power and high effective resolution. Thus adequate investigation of the physical conditions in the atmospheres of the brighter stars requires a spectroscopic dispersion of at least 3 A. per mm., and this is attainable with an exposure of reasonable duration only if the spectroscope is fed by a telescope with an aperture of six feet or greater. Again, knowledge of the structure of our own galactic system is dependent upon the observation of faint variable stars and upon star counts in sample fields down to the faintest limiting magnitude, while the dynamics of the system is most economically ascertained by the determination of the radial velocities of stars of the 8th and fainter magnitudes. These various modern investigations of the galactic system are within the reach only of those observers equipped with a very large instrument, and this is even more true of research on the extra-galactic systems. Nebular counts, determination of red-shift, and resolution of the nearer objects into their individual stars are the necessary preliminaries to any study of these distant objects, and all demand a large telescope. These various fields of investigation, and they comprise the greater part of modern stellar astronomy, are closed to astronomers in Britain because the largest telescope available here has an aperture of only three feet, that is, it has one-fourth the light-gathering power and one-half the space penetration of the telescopes which have been in use in increasing numbers in the United States and Canada during the last twenty-five years. Without at least one large instrument observational astronomy in this country must come to an end, except in such very narrowly restricted fields as astrometry and possibly solar physics.

Had there been no British observational astronomy in the period 1860 to 1920, the physical interpretation of stellar spectra might have been long delayed. Thus while in this period the stellar spectroscopy carried out in the United States was essentially concerned with the classification of stars by the appearance of their spectra and with the determination of radial velocities by the Doppler effect, it was Huggins and Lockyer in this country who first concerned themselves with discovering the chemical origin of the lines in stellar spectra, and in ascertaining, in modern phraseology, the degree

of ionization in the atmospheres of the brighter stars. This work was put on a quantitative basis by A. Fowler and received its atomic interpretation from Bohr's theory in 1914. As a result of his work in Fowler's laboratory in 1920, Saha gave a quantitative relation between the degree of ionization revealed by the stellar spectrum and the temperature and the pressure prevailing in the stellar atmosphere, while the elegant formulation of the theory by R. H. Fowler and E. A. Milne in 1924 was to some extent made possible by the stellar spectra available in the Solar Physics Observatory in Cambridge and to F. E. Baxandall's unrivalled powers of line identification. This quantitative interpretation of the stellar spectrum, probably the greatest achievement in astrophysics even up to the present time, was in its origin and its execution almost wholly a British achievement. It is perhaps not unreasonable to suppose that, if British astronomers had now the telescope which modern research requires, just as in the earlier period they had the best possible instruments of the time, they would again play the fundamental part in astronomical research which they did up to 1920.

Lacking at least one modern large telescope, the essentially British contribution to observational astronomy, so effective in the past, must inevitably disappear. Equally there will be a weakening of British supremacy in theoretical astronomy for, as in the case of the physical interpretation of stellar spectra, the theorist is most successful when he is working in almost day-to-day contact with the observer and his problems. Finally, the disappearance of observational astronomy here cannot fail to have an adverse effect on the whole British attack on the physical group of sciences. Thus in the past Balmer's and Rydberg's numerical description of line series depended upon Huggins's discovery, and measurement of the wave-lengths, of the ultra-violet hydrogen lines, while Bohr's theory was based upon and had its greatest triumph in Fowler's identification of certain stellar lines as being due to ionized helium. While it is difficult to foresee the future, there can be little doubt that the construction of the proposed telescope would give a great stimulus to the study of theoretical and applied optics, and that advances in nuclear physics would be influenced by a detailed knowledge of those transformations which are responsible for the energy generation in the stars. In the considered opinion of the Royal Astronomical Society there is, therefore, a case of overwhelming strength for the revival of British observational astronomy by the provision of at least one large reflecting telescope.

Use of a Large Telescope in Britain.—Climatic conditions in Great Britain are reputed to be so bad that a large telescope cannot be used here. Before any decision is taken to build a large telescope, this question must clearly be most closely examined. The weather imposes two limitations on the use of a large instrument. First, when it is clear, non-homogeneity of the Earth's atmosphere with its consequent variations of refractive index produces a corrugated wave front, so that a telescope, no matter how optically perfect, gives a tremor disk for a star of from one to five seconds of arc in diameter, instead of the theoretically expected Airy disk. This correspondingly involves a loss of resolving power for direct photography, and a great loss of light for spectroscopy since the narrow slit can only transmit a small fraction of the light incident in the large tremor disk. There is no evidence, however, to indicate that the size of the tremor disk experienced under average conditions in Britain is any greater than that obtaining on the west coast of the American continent and in South Africa, the places where most of the large telescopes in the world are at present located, and consequently there is no limitation due to " seeing " on the efficient use of a large instrument here. The fact that the first of the large telescopes were built and effectively used in the United Kingdom

(Herschel's four-foot reflector in 1789, Rosse's six-foot reflector in 1845, and Common's five-foot reflector in 1891) affords the strongest possible evidence that when it is clear in Britain large instruments may be used with their full effectiveness.

The second limitation lies in the limited number of nights when the sky is sufficiently clear to permit the use of any telescope. It cannot be denied that in this connection conditions in Britain are less favourable for the erection of an observatory than those in many other places in the world. Granted, however, that observational astronomy should be pursued in this country, the very infrequency of clear nights in itself demands the erection of the most efficient instrument, both optically and mechanically, in order that full advantage may be taken of such opportunities as there are for observation. At a site with many clear nights useful work can be done, both in the study of variable stars and in stellar spectroscopy, with a small and relatively inefficient instrument. Thus a 30-inch reflector can obtain a spectrum of adequate dispersion for the determination of the radial velocity of an 8th magnitude star with an exposure time of four hours, an exposure easily obtainable at a site with much clear weather, whereas in Britain, where the clear sky is frequently broken by clouds, it would be necessary to use an exposure time of the order of an hour, requiring a 72-inch reflector.

In point of fact paucity of clear nights is no insuperable handicap to the effective use of a large telescope. There is a great and ever increasing number of problems where the time spent at the telescope is a small fraction of that required for the work away from the telescope in the measurement of the photographic plates, the reduction and the subsequent discussion. A somewhat one-sided development of astronomy is necessarily entailed by the neglect of these problems, and this neglect is being forced upon astronomers at good sites by the necessity of preventing observation and subsequent discussion getting too greatly out of step. Examples of such problems are to be found in the average photometric investigation where perhaps not more than ten per cent of the total time spent is occupied by observation at the telescope, and in spectrophotometry where hundreds of lines are in some cases registered in a single exposure which takes up a very small fraction of one per cent of the total time required to complete the investigation. Even with a few clear nights in the year, one large telescope would provide opportunities for observation for the fully trained observers in the country.

The number of hours of clear night sky obtainable in a year in this country is not, however, hopelessly inferior to that obtainable in the countries where there are large telescopes.

Thus we have—

Mt. Wilson	(60- and 100-inch telescopes)	2700 hrs.
Victoria	(72-inch telescope)	1247 hrs.
Herstmonceux	(proposed 72-inch telescope)	1900 hrs.

The figure for Mount Wilson is the average for thirty-one years and that for Victoria is the average for twenty-one years. The Herstmonceux figure is based on sunshine records, assuming the conservative ratio 1·1 for the number of clear hours at night to the number of hours of bright sunshine. Thus the actual records suggest that we should get fifty per cent more time for observation at Herstmonceux than is obtainable at Victoria where the 72-inch telescope has been responsible for a greater output of work. This comparison of records is probably rather too favourable to Herstmonceux, since conditions at Victoria are such that clear conditions generally last throughout a whole night and for many nights consecutively. This state of affairs makes the planning of

observations and their execution at the telescope considerably simpler than when only a few hours are available in a night and these possibly broken by cloud. Making, however, the fullest possible allowance for this unfavourable factor, it is evident that if a 72-inch telescope can be used effectively in Victoria, then a similar instrument can be used with at least equal effectiveness at Herstmonceux.

Cost of Instrument and Organization of the Work.—The Royal Astronomical Society has not yet fully settled the details of the design of the proposed telescope. The problem is now under discussion by a committee of the Council and will form the subject of a symposium to be held at a special meeting of the Society in June. Two plans are under consideration. In the one there would be a 72-inch Cassegrain reflector of the conventional design together with a 27–40 inch Schmidt for direct photography, while in the other there would be a single universal instrument with a spherical mirror of 74 inches aperture, usable at will as a 49–74-inch Schmidt or as a condensing system with a clear aperture of 74 inches for stellar spectroscopy. Preliminary estimates received from Grubb, Parsons of Newcastle indicate that in either case the cost, including the building or buildings, would be of the order of £100,000.

Since so large a sum must be provided by H.M. Government, there is agreement that the proposed Isaac Newton Observatory should be erected at the new site of the Royal Observatory at Herstmonceux. This would ensure its location where observational conditions are probably as good as can be obtained in Great Britain, and at the same time secure the fullest economy in the costs of installation and maintenance. The cost of a separate site would be avoided, whilst library, workshop and other facilities would be available. Preliminary estimates suggest that a sum of £3500 per annum would be needed for running the Observatory; this would provide the salaries for a scientific director, working administratively under the Astronomer Royal, an assistant astronomer and a mechanic-night-assistant, together with enough money for actual maintenance.

It is an essential part of the scheme proposed by the Royal Astronomical Society that the telescope, or telescopes, should be available for observational use by the astronomers of the University and other established observatories in the country, as well as by the astronomers of the Royal Observatory itself. To ensure this it seems evident that the basic assignment of observing time at the telescope, or telescopes, would have to be in the hands of a Board of Management on which the various interested bodies would be represented. It has been suggested that the proposed Board of Management might be a committee of the Board of Visitors of the Royal Observatory with adequate representation from the Royal Astronomical Society.

An approach to H.M. Government for the required sum of the order of £100,000 need not, however, wait upon the settlement of these and other details.

Provided the application is granted, the Royal Astronomical Society would at an early date make definite recommendations to the Royal Society on the design of the telescope, or telescopes, and the best methods of organizing the work of the Isaac Newton Observatory.

Conclusion.—In this memorandum the Royal Astronomical Society has endeavoured to set out the need for at least one large telescope in this country. Failing the provision of such an instrument the Society fears that, except for a few highly specialized branches of the subject, observational astronomy will disappear in this country and accompanying that loss will be a great weakening of the theoretical astronomy which has been our great

contribution in the last quarter of a century. The Society has shown that the conditions of " seeing " in Britain impose no limitation on the efficient use of a large telescope here, while the number of clear hours at night is, if anything, in excess of that available at Victoria where a six-foot reflector is being most effectively used. The Society has considered the design and cost of the proposed instrument, or instruments, and suggestions for the most effective organization of the work.

In conclusion a notable step towards the revival of observational astronomy in this country would be taken if a grant of £100,000 were made for the construction of an Isaac Newton Observatory. The Royal Astronomical Society is confident that the Royal Society will give sympathetic consideration to this proposal, and ventures to express the hope that the application may be supported with all the influence and authority which the Royal Society can alone exert.

Second Memorandum, 1946 *September* 3.

The announcement, on the 15th of July by the President of the Royal Society, that the Chancellor of the Exchequer had agreed in principle to provide the money necessary to build a 100-inch telescope represents the greatest single contribution to the development of observational astronomy ever made in this country. The Council of the Royal Astronomical Society wishes to express its deep appreciation to the Royal Society for the careful consideration and acceptance of its first memorandum and for the care which must have characterized the representations of the Royal Society to H.M. Government.

In its first memorandum the Royal Astronomical Society undertook, if its application were granted, at an early date to make " definite recommendations to the Royal Society on the design of the telescope, or telescopes, and the best methods of organizing the work of the Isaac Newton Observatory ". The present, second memorandum is the fulfilment of that undertaking.

ORGANIZATION OF THE WORK OF THE ISAAC NEWTON OBSERVATORY

The Council of the Royal Astronomical Society has considered afresh the best possible methods of organizing the work of the Isaac Newton Observatory, and is of the firm opinion that the proposals outlined in the first memorandum offer, with one or two modifications, the most effective means of using the 100-inch telescope. In their modified form these proposals are that :—

1. The Isaac Newton Observatory should be erected at Herstmonceux, the new site of the Royal Observatory.

2. The Astronomer Royal, as head of the Royal Observatory, should have full administrative control of the Observatory, and scientific control under the direction of the Board of Management.

3. An independent Board of Management should be appointed to be responsible for the design of the telescope, to exercise general scientific direction over the Observatory and to ensure equitable use of the telescope by astronomers in the United Kingdom.

4. The staff proper of the Observatory should consist of two highly skilled technical assistants, responsible for servicing the telescope and assisting in the observation.

Since the Isaac Newton Observatory is to be the property of H.M. Government, economy and simplicity of operation require that it should be closely associated with the Royal Observatory. The new site of this Observatory at Herstmonceux ensures that the 100-inch telescope will thus be located at one of the most favourable astronomical sites in the country with the number of clear hours at night comparable with, if not in excess of, that prevailing at Victoria, B.C., where a large reflector has been in successful use since 1919. Since the Isaac Newton Observatory is for the use of all the observatories in the country, the working astronomers will in effect be provided by these observatories, and the only permanent staff required will be two technicians for servicing and maintaining the telescope and for assisting in the observation. In addition a scientific director will be required on the spot to advise the visiting astronomers on the most effective use of the telescope for their particular problems; in the opinion of the Council of the Royal Astronomical Society this function can be most satisfactorily filled by the Astronomer Royal. At the same time he must be the administrative head in order that the common services for the Isaac Newton Observatory and the Royal Observatory may be organized with the greatest economy and efficiency and with complete absence of friction. In the considered opinion of the Council astronomers in this country are fortunate beyond easy expression in having in Sir Harold Spencer Jones an Astronomer Royal not only willing to undertake this additional heavy responsibility, but who also combines the scientific and administrative ability needed to meet these exacting demands in the formative years of the new Observatory.

THE BOARD OF MANAGEMENT

The present and future Astronomer Royal will require the guidance of a strong and independent Board of Management. The functions of this body will be in the first instance to make arrangements for the design of the 100-inch telescope and, on its completion, in the words of the first memorandum " to ensure equal opportunities for the use of the telescope to the astronomers of all the observatories in the country ". The Council of the Royal Astronomical Society suggests that the Board of Management should consist of four ex-officio members, namely the Astronomer Royal (the director of the Royal Observatory), the Astronomer Royal for Scotland (the director of the Royal Observatory for Scotland), and the directors of the two largest university observatories, namely those at Cambridge and Oxford, together with three members appointed by the Royal Society, and three members appointed by the Royal Astronomical Society, each with a tenure of six years. It recommends that the chairman of the Board should be appointed by the Royal Society from amongst these ten appointed and ex-officio members. An ex-officio member should have the right to be represented by an alternate at any meeting of the Board which he is unable to attend.

The design and construction of the best possible 100-inch telescope will give rise to a number of problems for which neither an easy nor a quick solution can be expected. Experience elsewhere suggests that from five to seven years must elapse before the completed instrument is ready for operation. It is therefore of the utmost importance that a vigorous start on these problems should be made without delay, and the Council of the Royal Astronomical Society strongly urges that the authorization of the Board of Management by the Royal Society, and its appointment, be made at the earliest possible date.

DESIGN OF THE TELESCOPE

The design of the 100-inch telescope will be the responsibility of the Board of Management and of the Astronomer Royal. It will suffice, therefore, at this stage if the Council of the Royal Astronomical Society draws attention to a number of minimum requirements which should be satisfied in the final design. In the light of our present knowledge the greatest field of work for the telescope will lie in the detailed study of high-dispersion spectra (1 A. per 0·3 mm. and possibly greater). Such spectra are obtained with a large fixed spectroscope at the Coudé focus of the telescope, and the overriding requirement in the optical and mechanical design is that an image of a star in any part of the sky should be formed at the Coudé focus with the minimum number of reflections, that is with the least loss of light. Secondary requirements are that the telescope should also be usable for obtaining short-dispersion spectra (1 A. per 0·03 mm. and smaller), and for direct photography over the widest possible field.

Optical Design.—If stellar spectroscopy with both large and small dispersions were not only the most important, but also the sole requirement, there can be no doubt that the conventional optical system of a 100-inch paraboloid of *f* 5 focal ratio, with a number of small interchangeable Cassegrain hyperboloids, would be ideal. The construction of these systems is well understood, and has recently been greatly simplified by the use of the Burch image-compensator. The one disadvantage of this system is the small angular field covered with high definition—a marked limitation of the telescope for use in problems involving direct photography and objective prism spectroscopy. The possibility should not be immediately excluded of systems using a 100-inch spherical mirror which, with various non-hyperboloidal Cassegrains, would satisfy equally well all the requirements of stellar spectroscopy, which would not be more expensive to construct and which would offer certain possibilities for getting greatly extended fields for direct photography. Though the first choice of the Council is for the paraboloid-hyperboloid system, it recommends that the properties of the spherical-mirror systems should be carefully investigated before a final decision is reached.

Mechanical Design.—Three main types of mounting have been used for modern large telescopes. These are the fork-type, exemplified by the Mount Wilson 60-inch and proposed for the Lick 120-inch, the yoke-type as used in the Mount Wilson 100-inch and in a modified form in the Palomar 200-inch, and the crossed-axis type exemplified by the Victoria 72-inch, the Toronto and Radcliffe 74-inch telescopes, and the Texas 82-inch. With the ordinary fork a star image may be formed at the Coudé focus, with some mechanical weakening of the centre-piece of the tube, approximately as far as a meridian altitude of 75° with three reflections, but north of that only at the cost of five reflections. The same restrictions apply to the modified yoke-type, while still greater restrictions apply to the ordinary yoke as used in the 100-inch at Mount Wilson. So far only with crossed-axis mounting of the Texas and Radcliffe telescopes has the image of a star from any part of the sky been formed at the Coudé focus with four reflections. The fork- and yoke-type mountings, however, have a marked advantage over the crossed-axis type in being centrally symmetrical; they therefore require a smaller diameter dome or turret for the same focal length, and are much more easily used at the prime focus. The Council of the Royal Astronomical Society definitely favours the fork-type mounting for the 100-inch telescope, always provided that complete sky-coverage can be obtained at the Coudé focus with a maximum of four reflections, as for example in a tentative design by F. J. Hargreaves.

Two smaller points in connection with the mechanical design should be noted. Experience has shown the beneficial effects on optical performance of forced ventilation of the mirror-surface and the optical path, and this would allow the tube to be of the closed variety if desired, although a lattice tube could be employed if its sides were closed by thin sheet material to confine the stream of air. Again there can be no question of the improved performance of aluminized over silvered mirrors, so that an aluminizing plant should be included in the design of the telescope and dome, though this might be the property of and be operated by a commercial firm.

Controls.—The drive and controls in existing large telescopes exist in all degrees of refinement and complexity. Thus from 1910 to 1935 all large telescopes had the conventional clock drive and governor, but since then the Texas 82-inch, the Radcliffe 74-inch and the Palomar 200-inch have been provided with the McMath frequency controlled system with varying degrees of refinement. Similarly the controls may vary from the simple, directly read, coarse setting systems used in the Victoria 72-inch, the Toronto and Radcliffe 74-inch telescopes and the Texas 82-inch to the fine setting, remotely read and controlled systems as used in the Palomar 200-inch. There can be no question that fine-setting and remote-reading systems, involving Selsyn motors, afford the greatest possible efficiency in setting and guiding. This efficiency is only obtained, however, at the cost of exceedingly complicated electrical circuits, necessarily expensive and difficult to maintain, especially in a damp climate. Unbiased evidence can scarcely be expected from the designers and users of these various systems, and the Council of the Royal Astronomical Society recommends that before the final design is settled at least one competent astronomer from this country should be given the opportunity of assessing the performance and reliability of the systems of control used at Victoria, Texas, Mount Wilson and Palomar.

SPECTROSCOPES AND AUXILIARY EQUIPMENT

It cannot be too strongly emphasized that not only should the 100-inch telescope be designed and built so as to provide the most efficient light collector for the various spectroscopes, but also that the optical and mechanical design of these spectroscopes and other auxiliary equipment should proceed hand-in-hand with that of the telescope itself. Too frequently has it been true in the past that the Coudé spectroscope has been an afterthought with consequent and inevitable impairment of its efficiency and performance. There can be little question that this instrument should have a mirror collimator and various Schmidt cameras to give the widest possible range of spectroscopic dispersions. Easy interchangeability from one camera to another is of particular importance where the one instrument is to be used by a variety of observers. Preference undoubtedly will be given to an aluminium-on-glass grating with the greater part of the light in one order on one side, but large and readily changed prisms should be provided, especially for spectro-photometric problems. A Bowen image-slicer, improving the efficiency of a Coudé spectroscope by a factor of between five and ten, is clearly an essential part of the instrument, while provision should be made for crossing the spectroscope with a Fabry-Perot interferometer and an echelon. The Council of the Royal Astronomical Society strongly recommends that the advice and help of Dr Theodore Dunham of the Mount Wilson Observatory should be obtained at an early stage, since he has had extensive experience in the design and use of these instruments, and has already provided provisional designs of a completely interchangeable Coudé spectroscope for use at the Radcliffe Observatory.

A variety of spectroscopic problems requires a smaller linear scale than can be obtained at the Coudé focus of the 100-inch, and it is recommended that a Cassegrain and a focal plane spectrograph be provided. The design of these instruments is now fairly well standardized, and should afford no serious problems. In addition provision must be made at the Coudé and possibly at the Cassegrain focus for photoelectric equipment, while a double-slide plate holder with guiding telescopes or eyepieces for use interchangeably at the prime and Cassegrain foci is essential for all problems involving direct photography.

CONCLUSION

These requirements and suggestions on the design of the telescope and the spectroscopes are the result only of a preliminary and provisional survey of the problems involved. These are in fact the very problems which will demand the closest attention of the proposed Board of Management whose immediate authorization by the Royal Society and appointment is, therefore, of the first importance.

REPORT OF THE AUDITORS FOR THE YEAR 1946

We have examined the accounts of the Society and approve the various items of expenditure. It is with concern, however, that we view the large excess of expenditure over revenue, though a deficit was indeed anticipated in The Report of the Council to the previous Annual General Meeting of the Society.

We have checked the official list of Fellows against Subscriptions received and note with satisfaction a substantial rise over last year in active membership. This increase is in part due to payment of arrears by previous non-active Fellows, but excluding the effect of transfers from the non-active to the active list there remains an overall increase of some twenty Fellows.

We have inspected the premises of the Society. Those windows damaged by enemy action have been replaced temporarily pending the availability of better quality glass. We recommend that attention be given to improving the artificial lighting of the premises and that minor repairs to the carpet of the Upper Library be carried out.

In conclusion we wish to express our thanks to the Assistant Secretary who so helpfully furnished us with all the information and explanations we required.

H. F. FINCH.

V. C. A. FERRARO.

PROGRESS AND PRESENT STATE OF THE SOCIETY

	Patron	Institutional Members	Fellows: Compounders	Fellows: Annual Contributors	Fellows: Non-active Fellows	Associates	Total
1946 January 1	1	5	196	581	89	47	919
Since elected	...	...	+ 1	+ 47	...	− 5	...
Fellow elected 1945, counted as Annual Contributor, since compounded	...	...	+ 1	− 1	...	...	...
Fellow re-elected	...	...	...	+ 1	...	...	...
Fellowship resumed	...	...	...	+ 1	...	...	...
Fellow, election void 1943, ratified 1946	...	...	...	+ 1	...	...	...
Election void †	...	...	...	− 1	...	...	...
Deceased 1946	...	...	− 6	− 6	...	...	...
Deceased prior to 1946, death not notified	...	...	− 3	− 3	...	− 1	...
Resigned 1946	...	...	...	− 5	...	...	...
Since compounded	...	...	+10	−10	...	...	...
Suspense Account :—							
Added 1946 :							
(*a*) Fellows owing 6 guineas ...	...	...	...	− 3	+ 3	...	...
Deducted 1946 :							
(*a*) Deceased 1946—"War conditions"	...	...	...	...	− 2	...	...
(*b*) Deceased prior to 1946, death not notified—							
"War conditions" ...	...	...	...	...	− 2	−2	...
Bye-law 26A	...	...	...	...	− 1	...	...
(*c*) Resigned 1946—							
"War conditions" ...	...	...	...	...	− 3	...	...
Bye-law 26A	...	...	...	...	− 2	...	...
Transferred 1946 :							
(*a*) From "War conditions" 1945, to Active	...	...	...	+ 13	−13	...	...
(*b*) From Bye-law 26A 1945, to Active	...	...	...	+ 12	−12	...	...
(*c*) From Bye-law 26B 1945, to Active	...	...	...	+ 6	− 6	...	...
1947 January 1	1	5	199	633	51	49	938

(† Michael Edwin Chivers, elected 1946 June 14, election unratified.)

(N.B.—Eight Associates are also Fellows, and are therefore counted twice in the above table.)

Cash

RECEIVED

	£ s. d.	£ s. d.	£ s. d.
Balances, 1946 January 1 :—			
In hand of Assistant Secretary, on Petty Cash Account		11 16 11	
At Westminster Bank, on Current Account		468 8 7	
At Westminster Bank, on "B" Account :—			
A. S. Williams Bequest		52 10 0	
At Westminster Bank, on "C" Account :—			
Trust Funds	368 16 10		
Sales of Duplicate Books Fund	1 3 8		
		370 0 6	
At Post Office Savings Bank :—			
General Fund	2,704 18 6		
"C" Account	671 8 8		
Staff Pension Fund	355 14 7		
		3,732 1 9	
At London Savings Bank :—			
Ordinary Department (including £250 A. S. Williams Bequest)	1,127 16 6		
Special Investment Department	570 7 9		
		1,698 4 3	
			6,333 2 0
Redemption by Treasury of £500 2½ per cent. National War Bonds 1946/48 at par			500 0 0
Parliamentary Grant-in-Aid for Scientific Publications, received through the Royal Society for 1946			500 0 0
Dividends on Investments		643 7 1	
Interest on Savings Banks Deposits		129 6 8	
Income Tax refunded : 1945 April–December	146 5 8		
1946 January–April	93 0 0		
		239 5 8	
Sales of Publications :—			
For 1946	478 5 9		
Due in 1944	0 2 0		
Due in 1945	23 7 8		
1947 in advance	44 19 0		
		546 14 5	
Reprints :—			
For 1946	16 1 0		
Due in 1945	6 1 0		
		22 2 0	
Sale of photographs and hire of slides :—			
1946	10 17 10		
1945	0 14 0		
Franklin-Adams Charts	27 0 0		
		38 11 10	
Miscellaneous Receipts :—			
London Mathematical Society	30 0 0		
Assistant Secretary, contributions to Pension Scheme	23 19 0		
Excess on Contributions	0 10 7		
Postages repaid : 1944	0 0 2		
1945	0 12 0		
1946	31 7 1		
Postages 1947, paid in advance	3 6 6		
British Astronomical Association, 1945	12 10 0		
British Astronomical Association, 1946	39 5 9		
Editors of *The Observatory*, 1945	4 16 5		
		146 7 6	
			1,765 15
Received on Account of Contributions :—			
537 Annual Contributions, 1946	1,127 14 0		
3 Institutional Membership Fees	6 6 0		
35 Annual Contributions, 1947, in advance and 3 partial contributions	76 10 0		
2 Annual Contributions, 1948, in advance, and 1 partial contribution	4 16 6		
1 Annual Contribution, 1949, in advance, and 1 partial contribution	2 12 0		
44 Admission Fees, 1946	92 8 0		
44 First Contributions, 1946	81 18 0		
		1,392 4 6	
Arrears paid off :—			
1 1934–1936, written off and now repaid	6 6 0		
1 1939	2 2 0		
3 1940	6 6 0		
3 1941	6 6 0		
6 1942	12 12 0		
8 1943	16 16 0		
9 1944	18 18 0		
23 1945 (including 1 Institutional Membership Fee)	48 6 0		
1 Admission Fee and First Contribution, 1943	3 3 0		
7 Admission Fees and 6 First Contributions, 1945	22 1 0		
		142 16 0	
Compositions :—			
1 Initial (Fellow elected 1945 December)	47 5 0		
1 Initial (Fellow elected 1946)	47 5 0		
10 Reduced	156 9 0		
		250 19 0	
			1,785 19 6
"C" Account :—			
Dividends on Investments		171 16 10	
Income Tax refunded : 1945 April–December		21 14 2	
Interest on Post Office Savings Bank Account		16 15 8	
Sales of Duplicate Books and Instruments		15 16 6	
			226 3 2
			£11,110 19 10

Account

PAID

	£ s. d.	£ s. d.	£ s. d.
Office Staff : Salaries	597 0 10		
Income Tax on ditto	99 8 0		
Health and Unemployment Insurance	10 4 10		
Work for London Mathematical Society, 1945, 1946	15 0 0		
Assistant Secretary : Pension Premium (Society's contribution £45 ; Assistant Secretary's contribution £22 10s.)	67 10 0		
		789 3 8	
Porter and Wife : Wages and Cleaning (including charwoman)	255 4 3		
Income Tax on ditto	1 8 0		
Health and Unemployment Insurance	8 5 7		
Pension Contribution	13 0 0		
		277 17 10	
			1,067 1 6
Insurance		18 15 8	
Telephone		23 3 3	
			41 18 11
Printing, etc. :—			
Monthly Notices (Vol. **105**, Nos. 5, 6 ; Vol. **106**, No. 1)		574 9 5	
Reprints		34 0 1	
Miscellaneous		38 11 10	
Photo-engraving (*M.N.* £76 15s. 11d., *O.N.* £24 15s. 8d.)		98 8 7	
Printing specimens		5 15 6	
			751 5 5
Postages and Packing :—			
Distribution of *The Observatory*		23 12 7	
Monthly Notices, etc.		78 15 1	
Distribution of back numbers of *Monthly Notices*		53 14 11	
Office postages		86 6 1	
			242 8 8
Stationery and Office Expenses		95 18 11	
Heating and Lighting		150 8 2	
Accountants' Fee		21 0 0	
Subscription to Committee on Library Co-operation		1 1 0	
Subscription to A.S.L.I.B.		3 3 0	
I.A.U. Telegrams, 1945, 1946		20 19 2	
Authorized Travelling Expenses		9 3 5	
Repairs, Fittings and Fixtures		100 12 4	
House Expenses and Laundry		32 1 4	
Expenses of R.A.S. Meetings and Committees		41 5 2	
Porter's uniform		1 5 0	
Hire of cinematograph projector		5 5 0	
Bank Charges and Cheque Book		1 3 6	
Library Expenses		1 18 6	
Jackson-Gwilt master die and engraving of medal		4 3 6	
Gold Medal		10 7 6	
Miscellaneous Expenditure		18 3 6	
			517 19 0
Reproduction of Slides and Prints...			4 2 0
Purchase of Books from Potter Fund			16 8 9
Headley Observatory :—			
Rent of Observatory Paddock	5 0 0		
Insurance of Buildings and Instruments on site	1 6 6		
Mr. Maskell for care of site	6 13 4		
Repairs to Buildings	8 5 0		
		21 4 10	
Less Contribution from British Astronomical Association	5 1 11		
Contribution from Mrs. Phillips	7 6		
Contribution from Dr. Waterfield	1 13 4		
		7 2 9	
			14 2 1
Block Subscription to *The Observatory*			90 0 0
Expenses of Conversazione			146 1 4
Investment of £500 2½ per cent. Savings Bonds 1964/67 at par (received in exchange for National War Bonds)			500 0 0
Expenditure on Trust Accounts :—			
Turnor and Horrocks Fund (Library)		19 13 6	
Harry Watson Fund (Library)		26 7 1	
Jackson-Gwilt Medals (six purchased)		17 5 0	
Jackson-Gwilt Gift		25 0 0	
George Darwin Lectureship Fund		50 0 0	
			138 5 7
Balances 1946 December 31 :—			
In hand of Assistant Secretary, on Petty Cash Account		7 3 9	
At Westminster Bank, on Current Account, as per Pass Book	941 8 5		
Less Cheques not yet presented	37 6 4		
		904 2 1	
At Westminster Bank, on " B " Account (A. S. Williams Bequest)		52 10 0	
At Westminster Bank, on " C " Account :—			
Trust Funds £428 15 4			
Less Cheque not yet presented 5 3 6			
	423 11 10		
Sales of Duplicate Books Fund	17 10 7		
		441 2 5	
At Post Office Savings Bank :—			
General Fund (including £500 deposited 1946)	3,282 19 2		
" C " Account	688 4 4		
Staff Pension Fund at 1946 December 31 ... ... £355 14 7			
Add Deposited in 1946 ... ... 100 0 0			
Interest 1946 ... ... 8 17 6			
	464 12 1		
		4,435 15 7	
At London Savings Bank :—			
Ordinary Department (including £250 A. S. Williams Bequest)	1,156 0 0		
Special Investment Department	584 12 9		
		1,740 12 9	
			7,581 6 7
			£11,110 19 10

Dr. *General Fund Revenue Account*

	£ s. d.	£ s. d.
To Salaries and Wages, including Pension Premiums and National Insurance		1,046 19 0
„ Insurance and Telephone (after adjusting Reserves)		41 18 11
„ Printing, etc. (after adjusting Reserves)	1,819 9 5	
Less Amount received from the Parliamentary Grant-in-Aid for Scientific Publications through the Royal Society for 1946	500 0 0	
		1,319 9 5
„ Posting and Packing (after adjusting Reserves)		265 17 3
„ *General Expenses* (*after adjusting Reserves*) :—		
Stationery and Office Expenses	95 18 11	
Lighting and Heating	160 8 2	
Travelling Expenses	12 3 5	
Subscriptions to Committee on Library Co-operation and A.S.L.I.B.	4 4 0	
Accountants' Fee	21 0 0	
Gold Medal	10 7 6	
Expenses *re* Jackson-Gwilt Medals	4 3 6	
Office Furniture and Fittings, including repairs	234 12 4	
I.A.U. Telegram Service	7 17 10	
Sundries	95 3 4	
		645 19 0
„ Block Subscription to *The Observatory*		90 0 0
„ Purchase of Books from Potter Fund		16 8 9
„ Headley Observatory, Expenses *less* Refunds		13 11 0
„ Expenses of Conversazione (after adjusting Reserve)		148 1 4
„ Annual Reserve for Repairs		40 0 0
„ Reserve for Binding War-time Periodicals		50 0 0
„ Staff Pension Fund : Amount set aside for year		100 0 0
		£3,778 4 8

One Year to 1946 December 31 *Cr.*

	£ s. d.	£ s. d.	£ s. d.
By *Amounts received from Fellows* :—			
1 Arrear for 1934–36, written off and now repaid	6 6 0		
1 Arrear for 1939	2 2 0		
3 Arrears for 1940	6 6 0		
3 „ „ 1941	6 6 0		
6 „ „ 1942	12 12 0		
8 „ „ 1943	16 16 0		
9 „ „ 1944	18 18 0		
23 „ „ 1945 (including 1 Institutional Membership Fee)	48 6 0		
1 Arrear, Admission Fee and First Contribution, 1943	3 3 0		
7 Arrears, Admission Fees, 1945	14 14 0		
6 „ First Contributions, 1945	7 7 0		
537 Annual Contributions for 1946 (including 2 from Fellows deceased)	1,127 14 0		
3 Institutional Membership Fees	6 6 0		
27 Prepayments for 1946	56 14 0		
44 Admission Fees	92 8 0		
44 First Contributions	81 18 0		
		1,507 16 0	
Composition Fees :—			
Initial Fees	94 10 0		
Reduced Fees	156 9 0		
	250 19 0		
Less Transferred to Reserve Account	250 19 0		
	– – –		
Add Amount brought to Credit for the year	96 9 3		
		96 9 3	
			1,604 5 3
„ Interest and Dividends received (gross)		868 0 3	
„ Interest on Bank Deposit Accounts received		120 9 2	
			988 9 5
„ Sales of Publications, Photographs and Miscellaneous Receipts for the year			644 11 1
„ Deficiency one year to date			540 18 11
			£3,778 4 8

Note.—Fellows' 1946 Contributions not received were :—

32 Unobtainable under War conditions	67 4 0
12 Waived under Bye-law 26A	25 4 0
7 Waived under Bye-law 26B	14 14 0
28 Others unpaid at 1946 December 31	58 16 0
3 Admission Fees and First Contributions, ditto	9 9 0
2 Institutional Membership Fees, ditto	4 4 0
Total for the year	£179 11 0

This amount has been added to the Suspense Account and is not included in this Revenue Account.

Balance Sheet

	£ s. d.	£ s. d.
General Fund :—		
As at 1945 December 31	23,044 6 5	
Less Excess of Expenditure over Income, 1946	540 18 11	
		22,503 7 6
Trust Funds :—		
Capital as at 1945 December 31	5,207 0 3	
Income Balances at 1946 December 31	1,111 16 2	
Income Tax on Trust Funds, 1946 April–December, not yet refunded	19 10 8	
		6,338 7 1
Reserves :—		
Repairs and Maintenance :		
As at 1945 December 31 .. .. £200 0 0		
Add Set aside for 1946 .. .. 40 0 0		
	240 0 0	
Replacements of Photographic Slides and Prints :		
As at 1945 December 31 .. .. .. 195 7 8		
Add Sale Franklin-Adams Charts 27 0 0		
222 7 8		
Less Expenditure for the year 1946 .. .. 8 11 6		
	213 16 2	
Binding War-time Periodicals :		
As at 1945 December 31 .. .. .. 100 0 0		
Add Set aside in 1946 .. .. .. 50 0 0		
	150 0 0	
Sales of Duplicate Books Fund :		
As at 1945 December 31 .. .. .. 1 14 1		
Add Received from Duplicate Books and Instruments sold 15 16 6		
	17 10 7	
		621 6 9
Composition Fees Reserve Fund :—		
As at 1945 December 31	1,356 15 8	
Received in 1946	250 19 0	
	1,607 14 8	
Less 6 per cent. transferred to Revenue Account	96 9 3	
		1,511 5 5
Staff Pension Fund :—		
As at 1945 December 31	355 14 7	
Add Set aside in 1946	100 0 0	
Interest for the year	8 17 6	
		464 12 1
Amounts received in advance :—		
Contributions :		
1947 paid in 1945 .. .. £4 4 0		
1947 paid in 1946 .. .. 76 10 0		
1948 paid in 1945 .. .. 2 2 0		
1949 paid in 1945 .. .. 1 12 0		
1948 paid in 1946 .. .. 4 16 6		
1949 paid in 1946 .. .. 2 12 0		
	91 16 6	
Publications, 1947	44 19 0	
Postages, 1947	3 6 6	
		140 2 0
Sundry Creditors for Accounts due but not presented (including provision for printing publications for the year 1946, not yet completed)		1,784 0 11
		£33,363 1 9

To the Fellows of THE ROYAL ASTRONOMICAL SOCIETY.

We have examined the above Balance Sheet with the Books and Vouchers relating thereto explanations given to us.

We have verified the Securities representing the Investments and have found them to be

1946 *December* 31

	£	s.	d.	£	s.	d.
Investments :—						
General Fund, valued as at 1922 December 29 or subsequent cost ..	20,374	11	1			
Trust Funds, valued at cost	5,207	0	3			
				25,581	11	4
Debtors :—						
General	49	0	0			
Income Tax Recoverable :						
General Fund	131	13	2			
Trust Funds	19	10	8			
				200	3	10
Deposits at Savings Banks :—						
General Fund	5,488	4	0			
Trust Funds	688	4	4			
	6,176	8	4			
Cash on Current Account at Bank and In Hand :—						
General Fund	981	6	5			
Trust Funds	423	11	10			
	1,404	18	3			
As per Cash Account				7,581	6	7

Note.—Fellows' Contributions (including 2 Institutional Membership Fees) and 3 Admission Fees unpaid at 1946 December 31 : £732, 18s. 0d. This amount represents the total of the Suspense Account and is not included in this Balance Sheet.

£33,363 1 9

and certify it to be correctly drawn up therefrom and in accordance with the information and in order.

SUFFOLK HOUSE,
5 LAURENCE POUNTNEY HILL, LONDON, E.C. 4,
1947 January 28.

SHARP, PARSONS & CO.,
Chartered Accountants.

INVESTMENTS

As at 1946 December 31

General Fund

£2000 Swansea Corporation 3½ per cent. Stock.
£5125 London, Midland and Scottish Railway 4 per cent. Debenture Stock.*
£750 London, Midland and Scottish Railway 4 per cent. Preference Stock.*
£2400 Gas Light and Coke Co. 3 per cent. Consolidated Debenture Stock.*
£2000 Commercial Gas Co. 3 per cent. Debenture Stock.*
£496 Consolidated 4 per cent. Stock, 1957.
£1035 Agricultural Mortgage Corporation, Ltd., 4½ per cent. Debenture Stock, 1961–91.*
£1000 Hull Corporation 4½ per cent. Redeemable Stock, 1952–72.
£1000 Central Electricity Board 4½ per cent. Stock, 1957–82.*
£700 Birmingham Corporation 3 per cent. Inscribed Stock, 1947.
£2280, 5*s.* 3*d.* War Loan 3½ per cent. Inscribed Stock.
£500 New South Wales 4 per cent. Stock, 1942–62.*
£1156, 1*s.* 5*d.* Metropolitan Water Board 3 per cent. " B " Stock.
£500 National Defence Loan, 1954–58, 3 per cent. Bonds.
£500 Savings Bonds 2½ per cent., 1964/67.
£2118, 3*s.* 5*d.* Savings Bonds 3 per cent., 1960/1970. (Holding " A ")
£695, 16*s.* 0*d.* Conversion Loan 3½ per cent., 1961.

Trust Funds

£1004 Consolidated 4 per cent. Stock, 1957.
£965 Agricultural Mortgage Corporation, Ltd., 4½ per cent. Debenture Stock, 1961–91.*
£491, 10*s.* War Loan 3½ per cent. Inscribed Stock.
£1160, 16*s.* 3*d.* War Loan 3½ per cent. Inscribed Stock.
£542, 18*s.* 2*d.* Savings Bonds 3 per cent., 1960/1970. (Holding " B ")
£1122, 19*s.* 6*d.* Savings Bonds 3 per cent., 1960/1970. (Holding " C ")

* *Taxed at source.*

GIFTS TO THE GENERAL FUNDS AND PROPERTY OF THE SOCIETY

The John Lee Gift (1836 and 1844): In 1836 John Lee, Esq., LL.D., gave the Advowson of the living of Hartwell; in 1844 he gave the Advowson of the living of Stone, Bucks. In 1879 these Advowsons were repurchased by his heir, Edward Lee, Esq., for £700.

The Lawson Bequest (1856): Henry Lawson, Esq., bequeathed to the Society the sum of £200, free of legacy duty.

The Carrington Bequest (1876): R. C. Carrington, Esq., F.R.S., bequeathed to the Society £2000 Consols.

The Lambert Bequest (1877): C. J. Lambert, Esq., presented to the Society the sum of £500 free of legacy duty, being part of a sum of money bequeathed by his father, Charles Lambert, Esq., for scientific purposes.

The McClean Bequest (1905): Frank McClean, Esq., LL.D., F.R.S., bequeathed to the Society the sum of £2000, free of legacy duty.

The Farrar Bequest (1906): The Rev. A. S. Farrar, D.D., bequeathed to the Society the sum of £100, free of legacy duty.

The Parsons Gift (1922): The Hon. Sir Charles Parsons, K.C.B., F.R.S., gave to the Society £2500 War Stock 1929–47, in memory of his father, the 3rd Earl of Rosse, who made the 6-foot reflector, and who died 1867 October 31.

The Grove-Hills Bequest (1922): Colonel E. H. Grove-Hills, C.M.G., F.R.S., bequeathed to the Society, free of legacy duty, his collection of early astronomical and mathematical books up to the year 1700, together with a sum of £250 to cover the expenses incurred by the Society in connection with the books.

The Grove-Hills Fund (1922): In 1922 the Treasurer, Colonel Grove-Hills, collected by his private efforts, with the approval of the Council, a Special Fund to meet the immediate financial difficulties of the Society. The total amount received from all sources (including dividends on the investments representing the fund) has been £1913, 1*s.* 11*d.*, of which £1480, 2*s.* 10*d.* has been invested and is now represented by £535 Agricultural Mortgage 4½ per cent., £423, 15*s.* 11*d.* War Stock 3½ per cent. and £695, 16*s.* Conversion Loan 3½ per cent. 1961.

The Lindemann Bequest (1931): A. F. Lindemann, Esq., bequeathed to the Society the sum of £1000, free of legacy duty.

The Archdeacon Potter Bequest (1933) (*see below*).

The Goodridge Bequest (1936): Captain J. J. L. Goodridge, who died 1936 March 13, bequeathed to the Society the sum of £50, free of legacy duty. In 1937 the bequest was invested in £49, 0*s.* 4*d.* War Stock 3½ per cent.

The Herbert Spencer Bequest (1936): Herbert Spencer, Esq., who died in 1903, nominated the Royal Astronomical Society as one of twelve Learned Societies to be eventual beneficiaries of his residuary estate. His estate was wound up in 1936, and the Society's share of the residue amounted to £1241. The conditions of acceptance of the legacy were that the sum received should be spent in certain specified ways by the Governing Body within five years of the date of payment, and might not be used in any way for purposes of endowment. The bequest was finally expended during 1941.

The Lindley Bequest (1937): Miss Julia Lindley bequeathed to the Society the sum of £1000, free of legacy duty, which was received from the Public Trustee in the form of £1156, 1*s.* 5*d.* Metropolitan Water Board 3 per cent. " B " Stock.

The Stanley Williams Bequest (1939): A. Stanley Williams, Esq., who died 1938 November 21, bequeathed to the Society all his astronomical instruments, books, maps, photographs, manuscripts, etc., together with the sum of £200, free of legacy duty, for the reduction or publication of his observations of variable stars; and also a further sum of £100, free of legacy duty, for the furtherance of astronomy in general or of the Society in particular, in such manner as the Council of the Society may think fit. No expenditure from the fund has been made up to 1946 December 31.

The Plummer Bequest (1946): H. C. Plummer, Esq., M.A., F.R.S., bequeathed to the Society the sum of £1000 (to be invested and treated as a Trust Fund, the income to be at the disposal of the Council for all purposes) and made the Society a residuary legatee. No payment on this account has been received up to 1946 December 31.

SPECIAL FUND

The Archdeacon Potter Fund (1933): Archdeacon Beresford Potter, who died 1931 May 10, bequeathed to the Society a 3/88th share of his residuary estate. This legacy was received in 1933, and now stands invested in £300 3½ per cent. War Stock, the cash balance of £17, 15*s.* 2*d.* being expended on the library in 1934. The Council resolved to allocate the dividends from this fund for the purposes of the library.

	£	*s.*	*d.*		£	*s.*	*d.*
1946 Jan. 1. Balance of Fund...	48	5	7	1946. Purchase of Books ...	16	8	9
1946. Dividends, War Stock 3½ per cent.	10	10	0	1946 Dec. 31. Balance of Fund...	42	6	10
	£58	15	7		£58	15	7

TRUST FUNDS

The Lee and Janson Fund (1834 and 1879): In 1834 John Lee, Esq., LL.D., gave £100, and in 1879 T. C. Janson, Esq., bequeathed £200, the interest to be given to the widow or orphan of a deceased Fellow. These amounts now stand in £309, 16*s.* 3 per cent. Savings Bonds, 1960/1970.

	£	s.	d.		£	s.	d.
1946 Jan. 1. Balance of Fund ...	60	0	2	1946 Dec. 31. Balance of Fund :—			
1946. Dividends, 3 per cent. Savings Bonds	9	6	0	In P.O. Savings Bank	£37 9 2		
Interest on P.O. Savings Bank Deposit	0	18	6	At Bank	32 15 6		
						70	4 8
	£70	4	8			£70	4 8

The Turner Fund and the Horrocks Memorial Fund (1853 and 1876): In 1853 the Rev. Charles Turnor, M.A., bequeathed a sum of £500, which now stands in £430, 10*s.* 4*d.* 3 per cent. Savings Bonds, 1960/1970. In 1876 the Society received a sum of £318, 5*s.*, the unexpended balance of a fund collected for the purpose of erecting a memorial in Westminster Abbey to Jeremiah Horrocks: to this the Society added the sum of £55, 15*s.*, and the whole now stands in £95, 13*s.* 2*d.* 3 per cent. Savings Bonds, 1960/1970. The interest on these funds is to be used in the purchase of books for the library.

	£	s.	d.		£	s.	d.
1946 Jan. 1. Balance of Fund ...	4	13	4	1946. Purchase of Books ...	19	13	6
1946. Dividends, 3 per cent. Savings Bonds	15	15	8	1946 Dec. 31. Balance of Fund...	0	15	6
	£20	9	0		£20	9	0

The Hannah Jackson (née Gwilt) Fund (1861): In 1861 Mrs Hannah Jackson (*née Gwilt*) gave £300 Consols, which now stands in £287 3 per cent. Savings Bonds, 1960 1970; the interest to be given in medals or other awards in accordance with the terms of the Trust.

	£	s.	d.		£	s.	d.
1946 Jan. 1. Balance of Fund ...	46	17	3	1946. Purchase of Medals ...	17	5	0
1946. Dividends, 3 per cent. Savings Bonds	8	12	0	Gift awarded	25	0	0
				1946 Dec. 31. Balance of Fund...	13	4	3
	£55	9	3		£55	9	3

The Harry Watson Memorial Fund (1923): In 1920 Mrs Watson presented to the Society the sum of £300 as a memorial to her late husband, Lieut.-Col. Harry James Watson, F.R.A.S., the interest on this sum to be used for the purchase of books for the library, such books to be indicated by a special book-plate. This gift now stands invested in £542, 18*s.* 2*d.* 3 per cent. Savings Bonds, 1960/1970. In 1923 Mrs Watson bequeathed a further sum of £958, 17*s.* to the Society, which now stands invested in £965 Agricultural Mortgage 4½ per cent. Stock. The Council resolved that these two sums should together constitute a Trust Fund, to be designated *The Harry Watson Memorial Fund*, to be used for the purchase and binding of books.

	£	*s.*	*d.*		£	*s.*	*d.*
1946 Jan. 1. Balance of Fund ...	365	5	3	1946. Purchase of Books ...	26	7	1
1946. Dividends, Agricultural Mortgage 4½ per cent. ...	23	17	10	1946 Dec. 31. Balance of Fund:—			
Dividends, 3 per cent. Savings Bonds	16	5	8	In P.O. Savings Bank £239 12 4			
Income Tax, 1945 April–1946 April, refunded	21	14	2	At Bank 167 0 4			
Interest on P.O. Savings Bank Deposit	5	16	10		406	12	8
	£432	19	9		£432	19	9

The George Darwin Lectureship Fund (1926): In 1926 Sir James Jeans presented to the Society the sum of £1000 for the endowment of an annual lectureship, to be called *The George Darwin Lectureship*, the lecture to be on some subject of interest to astronomers, preference being given, in electing a lecturer, to one normally resident outside the British Isles.

This sum now stands in £1004 Consolidated 4 per cent. Loan. The income is annually applied to the purposes of the Trust in accordance with the terms of the Deed of Gift.

	£	*s.*	*d.*		£	*s.*	*d.*
1946 Jan. 1. Balance of Fund ...	140	19	11	1946 Oct. Lecture Fee ...	50	0	0
1946. Dividends, Consolidated 4 per cent. Loan	40	3	2	1946 Dec. 31. Balance of Fund:—			
Interest on P.O. Savings Bank Deposit	3	4	11	In P.O. Savings Bank £133 1 1			
				At Bank 1 6 11			
					134	8	0
	£184	8	0		£184	8	0

The A. G. Stillhamer Trust (1937): A. G. Stillhamer, Esq., of Bloomington, Illinois, left all his property outright to Miss Maude S. Capps, of Bloomington; but on account of certain personal memoranda and conversation between Mr Stillhamer and Miss Capps, the latter resolved to carry out what she believed to have been Mr Stillhamer's wishes by the payment to the Royal Astronomical Society of the sum of 2500 dollars in cash, the conditions of acceptance being that the principal is

to remain intact in the endowment fund of the Society, and the income therefrom to be used annually * to pay expenses of scientific research or to purchase definite scientific instruments for use in scientific instruction or research. The bequest has been invested in £491, 10*s*. War Stock 3½ per cent.

	£	*s.*	*d.*		£	*s.*	*d.*
1946 Jan. 1. Balance of Fund ...	144	18	5	1946 Dec. 31. Balance of Fund:—			
1946. Dividends, War Stock 3½ per cent.	17	4	0	In P.O. Savings Bank	£100 5 4		
Interest on P.O. Savings Bank Deposit	2	8	11	At Bank	64 6 0		
						164	11 4
	£164	11	4			£164	11 4

The E. W. Brown Trust (1939): E. W. Brown, Esq., M.A., Sc.D., F.R.S., who died in 1938, bequeathed to the Society the sum of five thousand dollars, and desired that the income from the bequest should be used for assistance in the calculation of accurate orbits of the bodies of the solar system, such income as should not be used for this purpose being used for the general purposes of the Society. The bequest was received in 1939 July, and was invested in £1160, 16*s*. 3*d*. War Stock 3½ per cent.

	£	*s.*	*d.*		£	*s.*	*d.*
1946 Jan. 1. Balance of Fund ...	277	0	9	1946 Dec. 31. Balance of Fund:—			
1946. Dividends, War Stock 3½ per cent.	40	12	6	In P.O. Savings Bank	£177 6 0		
Interest on P.O. Savings Bank Deposit	4	6	6	At Bank	144 13 9		
						321	19 9
	£321	19	9			£321	19 9

LIST OF PUBLIC INSTITUTIONS AND OF PERSONS WHO HAVE PRESENTED GIFTS (OTHER THAN BY EXCHANGE) TO THE LIBRARY DURING THE YEAR 1946

Abastuman, Astrophysical Observatory of the Georgian S.S.R.
H.M. Air Ministry
Astronomical Society of Mexico
Astronomical Society of South Africa
Astronomical Society of Tasmania
Baltic Geodetic Commission
British Association for the Advancement of Science Mathematical Tables Committee
British Council
British Interplanetary Society
Buenos Aires, Instituto Geografico Militar
Cambridge Instrument Company
Chinese Astronomical Society
Chinese Physical Society
Committee for the Distribution of Astronomical Literature
Copenhagen, Astronomisk Selskab
Czech Astronomical Society

* Miss Capps, subsequently to the initial conditions of the Trust, agreed to the income not being expended annually.

Danish Institute for Exchanges of Publications
Department of Scientific and Industrial Research
Erevan, Astronomical Observatory
Ghent, Sterrenkundig Instituut der Universiteit
Griffith Observatory, Los Angeles
Hyderabad, Nizamiah Observatory
Imperial Chemical Industries
Institute of Physics
International Astronomical Union
Kirkwood Observatory of Indiana University
Lille, Association Astronomique du Nord
Lourenço Marques, Technical Statistical Department
Maria Mitchell Association, Nantucket
Mathematical and Physical Society of Egypt
National Central Library
New York, Academy of Sciences
Peru, Society of Engineers
Pisa, Observatorio Geofisico " G. B. Donati "
Royal Canadian Air Force
Royal Society
Royal Society of Edinburgh
Santiago (Spain), Observatorio Astronomico
Scientific Instrument Manufacurers' Association
Society for Research on Meteorites
Survey of India, Geodetic Branch
Tashkent, University of Asia Minor
Washington, Carnegie Institution
Washington, National Bureau of Standards

Dr W. S. Adams
Professor H. Alfvén
Professor V. A. Ambarzumian
Dr W. Becker
Dr F. E. Brasch
Dr L. J. Comrie
Mr I. Corbu
Professor J. F. Cox
The Rev. Dr M. Davidson
Professor H. Dingle
Miss W. Eddington
Madame C. Flammarion
Dr A. Fletcher
Mr R. H. Garstang
Mr A. Giao
Miss M. F. Hardcastle
Professor O. Heckmann
Mr W. M. Holmes
Mr J. R. Irwin
Mrs B. S. Jeffreys
Professor H. Jeffreys
Mr H. I. Jensen
Mr R. Jonckheere
Sir H. Spencer Jones
Mr I. Jones
Mr V. I. Karmilov
Mr M. A. R. Khan
Mr J. Klepešta
Mr W. Krahulec
Mr F. C. Lamèch
Dr J. C. P. Miller
Professor L. M. Milne-Thomson
Mr M. Nicolet
The Editors of *The Observatory*
Mr G. Pallotti
Mr J. Péridier
The late Professor H. C. Plummer
Mr R. W. A. Ricketson

The Rev. A. Romañá, S.J.
Dr L. Rosenhead
Mr H. B. Rumrill
Mr P. M. Ryves
Professor F. Sacco
Mr D. H. Sadler
The Editors of *Sky and Telescope*
Mr C. T. Spencer
The Rev. Fr. J. Stein, S.J.
Professor F. J. M. Stratton
Professor E. Strömgren
Dr V. Vand
Mr C. J. Westland
Mr H. L. Willis

OBITUARY NOTICES

HISASHI KIMURA was awarded the Society's Gold Medal in 1936 for his valuable work on the Variation of Latitude. This was in fact his life-work and a comprehensive account of it was given by the President (Mr J. H. Reynolds) in his Address on the award (*M.N.*, **96,** 390, 1936; see also Frank Robbins, "The Royal Astronomical Society's Gold Medallist", *J.B.A.A.*, **46,** 266, 1936). Consequently the present notice records events in Kimura's life only since 1936. In 1936 he received Asahi-Sho (the Asahi-Award) which was given every year by Asahi-Shinbun-Sha, one of Japan's leading newspaper offices, to a few of the most eminent men in the country. Later the same year he received from the Emperor of Japan the Benka-Kunsho (The Culture Decoration), which is an order given to those who have contributed in the highest degree to the culture of the country. He received it along with two other scientists, Professor Nagaoka and Professor Honda. Also in 1936 he was elected an honorary member of the American Astronomical Society.

In 1941 Kimura retired from the directorship of the International Latitude Observatory of Mizusawa, and also from his membership of the National Research Council of Japan and of the committee of the Imperial Japanese Geodetic Commission. Thus his long official life was terminated, but not his astronomical studies. After removing his home from Mizusawa he began his new analysis of polar motion. He was very contented in his retirement, but his health was gradually declining. Although confined to bed for most of his last year he continued to devote long hours to his work on polar motion. He completed it only two days before his death just when Professor Tanakadate visited him to enquire after his illness. Its title was "New Study of the Polar Motion based on the Luni-Solar Actions (Second Paper)", the first paper having been published in 1926. Kimura asked Professor Tanakadate to read the paper for him at the general meeting of the Imperial Academy, and this he did on 1943 November 12. Kimura died of asthma on 1943 September 26 at the age of 74. His private life had been very happy. He is survived by his widow, three sons, one of whom is in Canada, and two married daughters.

Kimura was elected an Associate of the Society on 1910 June 10.

Y. HAGIHARA.

GEORGE WILLIS RITCHEY was born at Tupper's Plains, Ohio, 1864 December 31, and died at Azusa, California, 1945 November 4. He was elected an Associate of the Society in 1904.

Many names of those no longer with us are associated with the development of the reflecting telescope—Newton, Hadley, Short, Mudge, Herschel, Rosse, Lassell, Foucault, Draper, With, Calver, Brashear. Ritchey was of their company and a giant among them. He has left two enduring monuments to his genius—the two reflectors of Mount Wilson Observatory, the 60-inch and the 100-inch, which have been the spearheads of astronomy during the last thirty years. In addition to his almost magical skill as an optician he had great gifts as an inventor and engineer. He designed the mounting for the 60-inch and personally supervised its construction, and he figured its mirrors literally by himself. The 100-inch mounting was not entirely his responsibility, although many of his ideas were embodied in it.

Ritchey was a teacher of manual training in Chicago when Hale discovered him and asked him to join the staff of Yerkes Observatory. Hale had included a machine shop in the establishment, believing that astronomical instruments should be designed by astronomers and made under their supervision. Ritchey therefore had full scope for his abilities as inventor, designer and engineer, and he provided equal scope for optical work by setting up an optical workshop. With these facilities he produced the 24-inch reflector and the Snow horizontal telescope which included a coelostat with 30-inch and 24-inch plane mirrors and a 24-inch objective mirror. This telescope was afterwards set up on Mount Wilson and was in fact the first instrument to be used at the new Observatory.

Pursuing the same policy as at Yerkes, Hale provided machine and optical shops at Pasadena for the production of the large instruments that he planned for Mount Wilson. Here Ritchey carried out his real life's work. The figuring of the 60-inch mirror and its secondaries took him two years. By 1908 the telescope was in use and in Ritchey's hands it produced photographs of spiral and other nebulae which far surpassed in definition and quality any that had hitherto been seen. His close study of these photographs convinced him that the spiral nebulae were of the same character as the galactic system and enabled him to make estimates of the distances of the more conspicuous of them, which are not very different from those accepted today. The discovery of the image of a nova on a plate of M31 led him to take a series of photographs of this nebula at monthly intervals, which disclosed that novae occurred in the nebula about as frequently as in the galactic system. By this work alone he is entitled to a high place in the ranks of observers.

Ritchey was occupied for no fewer than six years in figuring the 100-inch mirror. He was doubtful from the first whether a really good mirror could be made from such a massive slab of glass, particularly as its quality was rather dubious; there were myriads of bubbles in the glass, arranged in layers, where the three successive pourings of molten glass had failed to unite completely. There was also reason to suspect a certain inhomogeneity. These doubts were only partly justified by the result and the optical quality of the 100-inch is little, if at all, inferior to that of the 60-inch when temperature conditions are favourable, as they all too rarely are.

The 100-inch was in use by 1917 and with it Ritchey obtained further photographs of spiral nebulae and also a series of photographs of the Moon which far surpassed in quality any that had been done before, and have not been equalled since. They show fully as much detail as can be seen with an 8-inch telescope.

Ritchey's experience with the 100-inch mirror led him to conclude that solid slabs of glass were unsuitable for very large mirrors and as an alternative he proposed a scheme for cellular mirrors built up from thin upper and lower plates, spaced apart by equally thin ribs of glass arranged vertically to form a series of square cells. Holes in these ribs placed all the cells in communication with one another and a current of air was to be passed through them while the mirror was in use to ensure that all its parts were as nearly as possible at the same temperature. The components were to be united by means of a synthetic resin cement.

Ritchey made a number of plane and parabolic mirrors on this principle, including a 60-inch. This last was made in France in collaboration with the Glaceries de la Compagnie de Saint Gobain, who had made the disks for the 60-inch and 100-inch mirrors and many others which Ritchey had worked.

These cellular mirrors were not completely successful; the finished optical surfaces

had a " quilted " appearance when examined under the knife-edge. This was doubtless due to elastic yielding of the top plate under the weight of the polisher in those parts not directly supported by the internal ribs. Moreover the cement was not so reliable as was hoped. Nevertheless the idea was sound in principle and it would undoubtedly be completely successful in a modified form made possible by recent advances in technique.

Ritchey was also a collaborator in the invention of a modification of the Cassegrain form of telescope designed to provide a wider field of good definition. In this modification (known as the Ritchey-Chrétien system) both the main mirror and the convex secondary have curves, the generators of which are not conic sections. On account of the difficulty of testing and figuring such curves this system has not come into general use; nowadays the Schmidt system and others allied to it are preferred. Ritchey claimed that if the 100-inch had been made as a Ritchey-Chrétien system, as he had wished, it would have been very much more efficient and its mounting would have been much smaller and more convenient in use.

Ritchey also proposed a very large " tower " telescope having a number of interchangeable mirror systems, one of the Schwarzschild type and the others of the Ritchey-Chrétien type. The main mirrors were to be of 315 inches aperture and the coelostat mirrors were to be larger still—470 and 400 inches diameter. All these mirrors were to be of the cellular type. The coelostat would impose a severe limitation of sky-coverage, but Ritchey proposed to overcome this by providing five such telescopes at 18° intervals of latitude, the central one to be on the equator.

An immense project such as this could not, as Ritchey well knew, be carried out in his lifetime, but he firmly believed that it was the proper way to carry out the next big advance beyond the 100-inch, and he believed that it was possible. An intermediate step in this advance (the equatorially-mounted 200-inch) has been taken on different lines and without Ritchey's participation; but his scheme remains as an inspiration and as a target for the future. Impracticable it no doubt was in his time, but it (or something like it) will not be impracticable in the future.

Ritchey had boundless enthusiasm as well as boundless patience and perseverance. In 1928 he addressed the Society on his plans for future large telescopes and those who heard him will not easily forget the forceful, almost apostolic fervour with which he expounded his views. Piety was another of his qualities, and his character shines out clearly in these of his published words :—

> " This is the incomparable exploration—the effort to bring the resources of " the Universe to the service of mankind. This series of telescopes, by revealing " to all men, *graphically*, by means of exquisite photographs, a Universe of which " the Earth, the Sun and the Milky Way are but an infinitesimal part, will bring " to the world a greater Renaissance, a better Reformation, a broader science, " a more inspiring education, a nobler civilization.
>
> " This is the Great Adventure. These telescopes will reveal such mysteries " and such riches of the Universe as it has not entered the heart of man to conceive.
>
> " The heavens will declare *anew* the Glory of God ".

F. J. HARGREAVES.

CHARLES EDWARD ADAMS, late Government Astronomer and Seismologist for New Zealand, died suddenly at his home in Wellington on 1945 October 31 at the age of 75. He was born at Lawrence, Otago, on 1870 October 1, being the son of Charles William Adams and Ellen Sara Adams. His father was a District Surveyor in the Lands and Survey Department, who, besides carrying out his duties in an efficient manner, showed considerable interest in geodesy. This exerted a considerable influence on him, and in later years father and son carried on much work together, sometimes in the form of weighty correspondence.

After his secondary education at Wellington College, Christchurch Boys' High School and the Otago Boys' High School, he entered Canterbury University College, where he gained his B.Sc. degree. During these undergraduate years he was a classmate of the late Lord Rutherford of Nelson and came under the influence of Professor A. W. Bickerton. Adams, who was an adept mathematician himself, often referred to the amazing manner in which Bickerton could produce mental results by means of his ability to remember graphs. After going through the School of Engineering at the same University and gaining his M.Sc. degree, he was appointed Lecturer in Mathematics at Lincoln College for several years.

His marriage to Eleanor Robina Jacobson of Akaroa in 1896 was the beginning of a wonderful partnership that was broken in most tragic circumstances in 1941 October by her death in an accident. Probably few men have been so broken in spirit as he was after that date, and although his death was not due to any sickness, his release ended a long suffering loneliness. His six children from this union have distinguished themselves in law, engineering, accountancy and teaching, while one grandchild, who is a Fellow of the Society, is showing keen astronomical interest.

The first few years after his marriage were extremely busy ones. He was employed at Napier by Kennedy Bros., Surveyors, and at Gisborne by George Grant, Surveyor, where he qualified as a surveyor. This was no light task in those days, as his work was done in the field often in parts of New Zealand little known at that time. In 1898 he joined the Lands and Survey Department at Napier; he was transferred to Wellington in 1900. This might be said to be the beginning of his scientific career, for as a computer his mathematical talent was given opportunity for expression, while as the officer in charge of the Tidal Survey he gave evidence of original thinking and ability for research work. After publishing papers on geodesy, survey computations, tidal factors, astronomy and even New Zealand mortality rates, he obtained his D.Sc. and became an Associate of the Institute of Actuaries.

In 1912 he was appointed Government Astronomer at the Hector Observatory, Wellington, renamed the Dominion Observatory in 1925. From 1920 until his retirement in 1936 he held the joint position of Government Astronomer and Seismologist. During this time his principal work was the maintenance of the New Zealand time service, and of seismological work in the Dominion. Perhaps his last official connection with survey work was his attendance at the Conference of Australian and New Zealand Surveyors held at Melbourne in 1912 May.

One of the brightest years in his life was the year spent at Lick Observatory, Mt. Hamilton, in 1915 as Martin Kellog Fellow. There he met all the famous American astronomers of the day, and so often did he recall with pleasure the many little incidents of that time that one began to feel that one knew them personally. He attended the first Pacific Coast meeting of the American Association for the Advancement of Science in 1915 August, and at the same time was elected a member of the Astronomical Society

of the Pacific at an informal meeting of the directors of the society held at the Students' Observatory, Berkeley; this was a momentous day for him. The main work undertaken at Lick by Adams was on the determination of the Moon's place by photography, but although he showed how this could be done successfully he did not follow it up on his return to New Zealand, mainly owing to lack of instruments.

Associations were again renewed when Adams, accompanied by his wife, joined the Crocker Eclipse Expedition led by Dr Campbell, to Wallal, Western Australia, for the eclipse of 1922 September 21. Here he was entrusted with the time signal and meteorological work of the expedition, as well as with the programme with the 40-foot camera. As a boy he had witnessed the New Zealand eclipse of 1885 September 8, and after the 1922 eclipse he was destined to lead the New Zealand expedition to Niuafo'ou Island in the Pacific for the eclipse of 1930 October 21. The party used a 19-foot coronagraph and a coelostat lent by the Society, and excellent photographs were obtained.

The effect of his long period as a surveyor showed itself in his astronomical outlook. He was more at home with a transit instrument and a computing machine than with any physical aspect of astronomy. His inclinations and talents were such that had he been given the opportunity he would have made worthy contributions to meridian astronomy. Computing comet orbits and ephemerides interested him greatly, and his contribution to this work is the use of the quantities P_x, P_y, P_z and Q_x, Q_y, Q_z for the heliocentric equatorial coordinates of a comet (*J.B.A.A.*, **32,** 231, 1922).

Many young astronomers owed their initial interest in astronomy, particularly on the computing side, to him, among them being L. J. Comrie, who became a professional computer. He showed a great willingness to make anything available to anyone who was interested in astronomy. In this manner, together with several enthusiastic amateurs of the time, he founded the New Zealand Astronomical Society in 1920; as Secretary over a long period and President on two occasions, he guided its destiny to within a few years of his death.

Through his efforts a 9-inch photovisual refractor was purchased by the Wellington City Council and an unpretentious but useful galvanized iron building known as the Wellington City Observatory was officially opened on 1924 August 26. He acted as Honorary Director for the whole of its existence and made the telescope available to anyone willing to use it. For many years he endeavoured to have a fund held by the New Zealand Institute (now the Royal Society of New Zealand), known as the Carter Bequest, used for its purpose of building a suitable observatory. With the help of many others inspired by him, his ambition was realized when the Carter Observatory was officially opened on 1941 December 20, replacing the old City Observatory. He became one of the original members of the Observatory Board.

For some years he was secretary and then a council member of the Wellington Branch of the New Zealand Institute; he also held office in the astronomical section of the same body.

He was a prominent Freemason, being initiated in Scinde Lodge, Napier, in 1898. Upon coming to Wellington he joined Aorangi Lodge, and was installed as Master in 1908. From 1910 to 1941 he acted almost continuously as secretary.

He was elected a Fellow of the Society on 1909 November 12.

I. L. THOMSEN.

CHARLES FREDERICK BUTTERWORTH was born on 1870 November 29 at Stretford, Lancashire, receiving his education in Manchester. He himself wanted to study chemistry but owing to the wish of his father, Francis Joseph Butterworth,

he entered the cotton trade instead, leaving school at the age of 15 and working his way up through all the grades of this business.

His astronomical interests must have begun early for he was a foundation-member of the Société Astronomique de France which was founded in 1887. It was not however until 1910 that he joined the British Astronomical Association and that his productive work as an observer began. His main interest lay in the observation of variable stars. At Poynton, Cheshire, he put up a 6-inch Grubb equatorial refractor (moved on his retirement in 1927 to Port St. Mary, Isle of Man), which was the instrument he used throughout, supplemented at times by a 10¼-inch and a 15-inch reflector, though he only used these rarely and never after 1927.

His observations of Long Period and Irregular Variables communicated to the Variable Star Section of the British Astronomical Association between 1911 and 1941 amounted to just under 80,000. This series was particularly remarkable for the uniformly high proportion of early morning observations, a period during which most amateur observers find it difficult to be active owing to the calls of their professions. As a result he was able to achieve a much greater completeness in his observations than is granted to most. Herein too lies their special value, coupled with the great care with which they were made, the continuity in instrument and method and the stimulating example they afforded to others.

In addition to the above he was also a member of the Association Francaise d'Observateurs d'Etoiles Variables and sent to this organization a great number of observations of stars not on the programme of the British Astronomical Association.

It is a measure of his tenacity of purpose that during 30 years of observing he made on the average more than 10 light estimates a night—a very remarkable performance if all circumstances be considered and one which puts him quite in the forefront of English variable star observers.

For the above work he received in 1927 the first Abbot Silver Medal from the University of Lyons and in 1928 was awarded the Palmes d'officier de l'Académie by the President of France. In 1941 he was awarded the Walter Goodacre Medal and Gift of the British Astronomical Association.

From 1913 to 1920, as a member of the Spectroscopic Section of the British Astronomical Association, he contributed to its Journal several papers on work done with a 6½-inch prismatic camera on Mira Ceti, Comet Delavan (1913 *f*), γ Cassiopeiae, N Aql III (1918) and N Cyg (1920).

But astronomy was not his only interest. He was an extremely keen cellist and pianist and spent a great deal of time on chamber music, especially string quartets, having acquired a very fine set of old Italian instruments to ensure balanced tone in the ensemble. Ornithology too made its call on part of his time as did botany and geology. A yacht and the growing of roses were further occupations.

He died at Port St. Mary on 1946 September 22. He was twice married and leaves a widow.

In all he did his business-like habits and a very fine memory enabled him to achieve results above the average. If to his keenness in not wishing to lose a single night's observation we owe a great debt from an astronomical point of view there will be many who will have regretted not meeting in consequence one who so evidently had much to give.

He was elected a Fellow of the Society 1918 December 13.

W. M. LINDLEY.

CHARLES STUART CUSHING was born on 1867 December 28 in San Francisco of pioneer parents. After graduating from the Oakland High School he spent some time in the banking business but soon turned to his lifetime profession of the law; he went into partnership with his brother and practised for fifty years in San Francisco.

His interest in astronomy was aroused by going with a party to view the total solar eclipse of 1889 January 1 in northern California. As a result of that occasion the Astronomical Society of the Pacific was formed. Cushing was one of its earliest members and loyally served its best interests until his death on 1946 January 7. Sixty years ago it was possible for some critics to point out that California, despite its clear skies, was not doing as much for astronomy as some more settled parts of the world. Cushing, in his support of the Society as a layman, played a notable part in answering this challenge and developing astronomical interests outside professional circles; the importance of this aspect of the evolution of astronomy, especially in the provision of large Californian telescopes, can hardly be over-emphasized. Especially valuable to the Astronomical Society of the Pacific was his service as Chairman of the Finance Committee and on his death he bequeathed a considerable sum of money to the Society. He was twice President, in 1907 and 1921, and on the latter occasion delivered an eloquent address on the award of the Bruce Medal to Sir Frank Dyson. Shortly before this he had visited Europe and made a tour of observatories in this country, France and Italy.

He was elected a Fellow of the Society at the time of the centenary celebrations in 1922.

Cushing had wide interests in life, including agriculture, history (especially of California and its pioneer days) and politics and enjoyed a wide acquaintance of friends, his greatest being his wife with whom he spent a long and happy life.

KIYOTSUGU HIRAYAMA was born on 1874 October 13, the only son of a ship-architect in Sendai. Although of the same surname, he was not related to Shin Hirayama. After a distinguished record as a student, Kiyotsugu Hirayama completed the course in astronomy at the Tokyo Imperial University in 1897. During the next few years he did some school-mastering and also made some latitude observations at the Azabu Observatory for checking the observations at Mizusawa. He was a member, along with Shin Hirayama, of the eclipse expedition to Sumatra in 1901. In 1906 he was appointed Assistant Professor of Astronomy in the Tokyo Imperial University. He assisted Professor Terao, Director of the Tokyo Astronomical Observatory, Azabu, Tokyo, in the computation of Japanese national almanacs. On Terao's retirement in 1920 he was appointed to the Chair of Astronomy in the University and taught a variety of courses covering the whole field of classical astronomy until his own retirement in 1935 at the age of sixty. From 1921 to 1928 he was associated with the bigger and newly established Mitaka Observatory and superintended the almanac computations there. In 1935 he was elected a member of the Imperial Academy of Japan.

Early in his scientific career, Hirayama began to study the problem of latitude variation as a result of his experience as an observer in this field. He attributed the Z-term to systematic errors due to the flexure of the zenith telescope but his conclusion is still open to criticism (*A.N.*, **176,** 1907; **179,** 1908; **181,** 1909). He published a paper discussing the declinations and the proper motions of 246 stars, for which he was given his doctor's degree in 1911. During 1905–1907 he was on the committee for determining the latitude 50° at Sakhalin and was awarded St. Anna's decoration by the Russian government (*Proc. phys.-math. Soc. Japan*, ser. ii, **4,** 1907).

Oriental classics was a hobby of his. He searched the records of Halley's comet (*Observatory*, **33**, 1910), comet AD 373 and 374 (*Observatory*, **34**, 1911) in Japanese history and of the Leonid meteors in Japanese and Chinese classics (*Observatory*, **52**, 1929) and discussed Fisher's work at Harvard. He also studied ancient eclipses and made many computations on eclipse records in the Chinese classics Shu Ching and Shih Ching (*Proc. phys.-math. Soc. Japan*, ser. ii, **8**, 1915).

In 1916 Hirayama was sent abroad by the Japanese government to work in America. He first went to the Naval Observatory in Washington for work on almanac computation. His interest in the lunar theory, which he had cherished since his student days by reading Tisserand over and over again, then led him to work under E. W. Brown in Yale and to assist in the heavy computations of Brown's lunar table. During his stay in Yale he was in close contact with Schlesinger.

Following the advice of Brown he began to work on the asteroids. The first successful attempt was a modification and simplification of Brown's theory of libration of asteroids (*J. Coll. Sci. Tokyo*, **41**, 1917). He made clear the transition of libration to revolution and *vice versa* in the motion of an asteroid and proposed a hypothesis of a resisting medium for the explanation of the gaps in the distribution of the mean motion of asteroids, which unfortunately he himself had finally to withdraw in a later paper (*Proc. imp. Acad. Japan*, **9**, 1933). His theory of libration was later applied to the motion of Hecuba and proved its legitimacy by the actual numerical computation of Wilkens. In fact Hirayama pointed out, at the same time as Hagihara, the incorrect view of Wilkens that Wilkens's computation showed the asymptotic behaviour in the secular recession of Hecuba's mean motion from the exact commensurability with Jupiter's mean motion (*A.J.*, **38**, 1928; *Proc. phys.-math. Soc. Japan*, **10**, 1928). This view of Wilkens's was proved to be misleading by Wilkens's own further computation. In his last published paper Hirayama computed with the assistance of Akiyama the orbit of Hilda for over eighty years' interval. The object was to obtain an idea of its libration by the method of special perturbation of the Keplerian elements with a view to avoiding the difficulty in the question raised by Sundman of convergency of the expansion of the disturbing function in the case of Hilda (*Proc. imp. Acad. Japan*, **13**, 1937; *Jap. J. Astr. Geophys.*, **15**, 1937). Hirayama's theory of libration again proved to be completely in agreement with the actual computation, although the time-interval for which he computed the motion covered only about a half of its complete period of libration. Hirayama also pointed out Klose's misconception that the existence of the gaps in the distribution of asteroidal mean motions is due to the presence of small divisors (*A.N.*, **218**, 1923; **221**, 1924).

In face of the serious problem of the existence of the gaps he came after some struggle to the discovery of the existence of the families in the asteroids, Themis, Eos, Coronis, Maria and Flora. The numbers belonging to each of these families are counted respectively to be 34, 38, 23, 16 and 81 on the data secured until 1933, and the mean motions are respectively around 641″, 678″, 728″, 873″ and 1076″. He called the secular parts of the eccentricity and of the inclination free from the perturbation due to the major planets by the name of the proper eccentricity and the proper inclination respectively. The difficulty is that the elements he took were not quite free from periodic perturbations. Further the correlation between the magnitude of an asteroid and the deviation of an individual mean motion from the mean for the asteroids belonging to the family has shown that, the fainter the asteroid is, the larger becomes the deviation

and accordingly he was led to the hypothesis that asteroids are the product of fragmentation of a mother planet, on the basis of equipartition of energy to individual bodies. This hypothesis has been discussed from various points of view, for example, on the ground of probability (*Proc. phys.-math. Soc. Japan*, ser. ii, **9**, 1917; ser. iii, **1**, 1919; **2**, 1920; *A.J.*, **31**, 1918; *Jap. J. Astr. Geophys.*, **1**, 1922; **5**, 1927; *Scientia*, **31**, 1922; *Proc. imp. Acad. Japan*, **9**, 1933). This grouping of asteroids, with its possible connection with their origin, was a brilliant discovery, even though an antagonistic view was maintained by Brown. Nevertheless a satisfactory explanation for the existence of the gaps is still needed and open to further investigations as an unsolved serious problem in dynamical astronomy.

Hirayama published a paper on the motion of a retrograde planet by extending Laplace's theory of secular perturbation, independently of Moulton (*Proc. imp. Acad. Japan*, **3**, 1927).

In accordance with the programme of the *Astronomisches Rechen-Institut* he computed with Akiyama the definitive orbits of several asteroids and their ephemerides (*Proc. imp. Acad. Japan*, **3**, 1927; **4**, 1928; **5**, 1929; **6**, 1930; **7**, 1931; **10**, 1934).

Hirayama also worked out the motion of a star in a nebulous cloud, as in Brown's paper which had appeared earlier in the *Astrophysical Journal*, on a dynamical basis and applied the theory to an explanation of periodic variable stars of Cepheid and U Geminorum types. The theory is, however, hardly acceptable at present when we have numerous astrophysical and spectroscopic data at our disposal (*Proc. imp. Acad. Japan*, **7**, 1931; **8**, 1932).

After he retired from his professorship he was eagerly engaged in the study of the history of astronomy in Japan. He never published his results, but only talked about them at the colloquia at the Azabu Observatory.

He served as vice-chairman of the astronomy section of the National Research Council of Japan from its earliest days. He was present at the I.A.U. meetings at Cambridge in 1925 and at Boston in 1932 and observed the eclipse in Maine, U.S.A.

Hirayama died on 1943 April 8. He is survived by the elder of his two sons, an engineer, and his two daughters. His wife, an earnest Christian and greatly devoted to him, and his second son, died about a year earlier. He was elected a Fellow of the Society on 1926 February 12.

Y. HAGIHARA.

SHIN HIRAYAMA, died on 1945 June 2, and his death has removed one who has played a leading part in the progress of astronomy in Japan. He died in his lonely refugee home at a small village in Suwa, a mountain district about eighty miles west of Tokyo, just after hearing of the complete destruction of such peaceful scientific institutes as the Azabu Observatory, Tokyo, and the bigger Mitaka Observatory, Mitaka-Tokyo, which he had built and cherished so enthusiastically and effectively, as poor victims of the hateful and merciless world war. His funeral was held amidst a heavy air-attack in the desolate and devastated capital of Japan.

Shin Hirayama was born as a second son of a former guard of Shōgun on 1867 September 9, in Tokyo. After finishing the course of astronomy in the Tokyo Imperial University in 1890 he was sent by the Japanese government for further study in astronomy to England. He came to the Royal Observatory, Greenwich, for work on astronomical spectroscopy just in its infancy at that time. After several months' stay in England, Huggins advised him to work with Vogel at Potsdam for the study of astrophysics, as Vogel had better equipment than Huggins. Hirayama then went to Potsdam and

stayed in Germany about three years. He attended the lectures and seminars in Berlin and Leipzig such as those of Kuffner, Tietjen, Scheiner, Bruns and even of Sophus Lie. During his stay in Germany he published a paper describing his experiments on various diffraction patterns with Scheiner (*Abhang. preuss. Akad. Wiss.*, **1**, 1894). In Potsdam he worked in the same room with Schwarzschild, who was a Privatdozent in the Berlin University at that time. Hirayama met Frost and Ludendorff, who came to Berlin as students after Hirayama. He loved Wannsee, which might be why he chose Suwa as his refugee home.

He came back to Japan in 1895 and was made a professor of practical astronomy in the Tokyo Imperial University and taught practical astronomy, astrophysics, stellar astronomy, orbit determination and geodesy in the University. In 1919 he was appointed Director of the Tokyo Astronomical Observatory and eagerly engaged in promoting astronomy in Japan, at the same time as in completing the equipment and organization of the Observatory. He built in 1924 a larger national observatory, though still belonging to the University, at Mitaka, a suburb of Tokyo. He installed the tower telescope of the Potsdam type and the 26-inch equatorial refractor of Babelsberg type, and organized an almanac office in the Observatory. In 1928 he retired from the professorship and the post of the director at the age of sixty.

Meanwhile Hirayama was the chairman of the astronomy section of the National Research Council of Japan and promoted the cooperation in astronomical work both at home and abroad. He visited observatories in Europe and America in 1912 and was present at the I.A.U. meetings in 1922 at Rome, in 1928 at Leiden and served as a vice-president.

Hirayama acted as the chairman of the Geodetic Committee of Japan. The organizations of the International Latitude Service Station at Mizusawa, where Kimura's famous work was carried out, and the installation of the International Time Service Station at Mitaka, where Miyadi discovered the longitude variation due to the herpolehode motion of the Earth's pole, were also due to Hirayama. As to the latter, he successfully resisted the pessimistic view on the possibility of radio communication with Europe on the part of electrical engineers.

He took his doctor's degree in 1899 and was elected a member of the Imperial Academy of Japan in 1909.

Hirayama's published work began with the study of sunspots. He collected records of sunspot observations in Chinese classics and communicated them to the *Observatory*, **18**, 1889. He also worked on solar rotation, systematic spot motion, and the harmonic analysis of sunspot numbers (*J. Coll. Sci. Tokyo*, **3**, 1890; **32**, 1912; *Proc. phys.-math. Soc. Japan*, **4**, 1890; ser. ii, **3**, 1906; **7**, 1914; *A.J.*, **9**, 1890) and published a theoretical paper on the absorption and scattering in the solar atmosphere after Schwarzschild (*Proc. phys.-math. Soc. Japan*, ser. ii, **9**, 1918). He joined eclipse expeditions to Hokkaido in 1896, to India in 1898 and to Sumatra in 1901 (*Ann. Obs. Tokyo*, **3**, 1, 1901; **3**, 2, 1903; *Proc. phys.-math. Soc. Japan*, ser. ii, **1**, 1901; *J. Coll. Sci. Tokyo*, 1897). For some time he was engaged in studying the colour effect of the constant of astronomical refraction (*Proc. phys.-math. Soc. Japan*, ser. ii, **4**, 1908). He secured good photographs of Comet Morehouse (*Ann. Obs. Tokyo*, **3**, 6, 1910). Much time was spent by Hirayama on a study of meridian transits by photographs at the earliest epoch of its development (*Ann. Obs. Tokyo*, **3**, 4, 1903; **5**, 2, 1911; *Proc. phys.-math. Soc. Japan*, ser. ii, **8**, 1916). He discovered the asteroids Tokio and Nipponia (*A.N.*, **152**, 1900; **164**, 1904; **177**, 1908). And after these discoveries he bought a Brashear's

photographic camera with which Oikawa discovered thirteen new asteroids at the Mitaka Observatory.

Hirayama was interested from his early career in the problem of two bodies (*A.J.*, **9,** 1889; *Proc. phys.-math. Soc. Japan*, **4,** 1890). He developed a modification of Gibb's method for the ratio of triangles in Gauss's theory of orbit determination by developing the radius vector in Fourier series instead of in power series of time as in Gibb's method (*M.N.*, **62,** 1902; **66,** 1906; *Proc. Jap. Ass. Adv. Sci.*, **2,** 1916). He had an unpublished paper on a new method for orbit determination at which he worked a few years before his death, but the manuscript was burnt in the Azabu Observatory in an air-raid.

Later in his scientific career he devoted himself to stellar astronomy. He published papers on the mean distance of stars of different spectral types (*Proc. phys.-math. Soc. Japan*, ser. ii, **2,** 1918; *Ann. Obs. Tokyo*, Appendix 10, 1922), on the correlation of space velocity of stars of different spectral types to their absolute magnitude (*Proc. Imp. Acad. Japan*, **6,** 1930), on the solar motion and the stream motion from radial velocities (*Jap. J. Astr. Geophys.*, **9,** 1931), on the centre of star-systems of different spectral types (*Proc. Imp. Acad. Japan*, **8,** 1932), and on the apparent distribution of stars of different longitudes along the galactic equator (*Jap. J. Astr. Geophys.*, **10,** 1932).

He was the first to apply Darwin's method of tidal analysis to Japanese ports (*J. Coll. Sci. Tokyo*, **28,** 1911). He also published a new geometrical classification of long period variable stars (*Jap. J. Astr. Geophys.*, **2,** 1924).

Hirayama was extremely enthusiastic in promoting astronomical research in Japan. There is nothing in Japanese astronomy which did not come under his inspiring influence. But it was to the development of the Azabu and Mitaka Observatories that he devoted his life and the news of their destruction literally brought his life to an end.

He had outlived his devoted wife by twelve years and in his loneliness his only consolation was to come to the Azabu Observatory, there to discuss astronomy, astronomers and observatories with his former pupils. He had three sons and four daughters. His second son is a professor of architecture and his third son a geologist.

Hirayama became a Fellow of the Society on 1891 February 13 during his stay at Greenwich, and was elected an Associate on 1923 November 9.

Y. HAGIHARA.

Sir JAMES HOPWOOD JEANS was born at Southport on 1877 September 11. He was the son of William Tulloch Jeans, of Tulse Hill, the father's profession being that of parliamentary journalist. He was educated at Merchant Taylors' School from 1890 to 1896. He went up to Trinity College, Cambridge, as a Scholar in 1896, read mathematics, and was bracketed Second Wrangler in the Mathematical Tripos of 1898 with J. F. Cameron, now Master of Gonville and Caius College. He took a First Class in Part II of the Mathematical Tripos in 1900, and was awarded an Isaac Newton Studentship. He won a Smith's Prize in 1900, and was elected to a Fellowship at Trinity in 1901. He was appointed University Lecturer in Mathematics in 1904, but became Professor of Applied Mathematics at Princeton, New Jersey, in 1905, holding the Chair there till 1909. It was at this period that he published his well-known text-book " Theoretical Mechanics " (1906). He returned to Cambridge as Stokes Lecturer in 1910, but resigned the post in 1912. Thereafter he held no teaching post for the rest of his life, though he was appointed Professor of Astronomy at the Royal Institution in 1935 and was annually re-elected to the Professorship until he resigned from ill-health in 1946.

He was awarded the Adams Prize of the University of Cambridge in 1917 for an essay entitled " Problems of Cosmogony and Stellar Dynamics ", which was published in 1919. In 1922 he delivered the Halley Lecture at Oxford on the subject " The Nebular Hypothesis and Modern Cosmogony ". In 1923 he was appointed a Research Associate of Mount Wilson Observatory. In 1925 he delivered the Rouse Ball Lecture at Cambridge under the title " Atomicity and Quanta " and in 1930 the Rede Lecture, under the title " The Mysterious Universe ".

He was awarded the Gold Medal of the Royal Astronomical Society in 1922, and served as President for the two years 1925–1927, delivering in that period three Presidential Addresses, on the respective occasions of presenting the Society's Gold Medal to Sir Frank Dyson (June 1925), Einstein (February 1926) and Schlesinger (February 1927). In 1927 the Royal Astronomical Society founded the annual George Darwin Lecture, the endowment for which was presented by Jeans, who thus desired to commemorate the famous mathematical astronomer who had been such an inspiration to him.

Jeans was elected a Fellow of the Royal Society in 1906, at the early age of twenty-eight. He gave its Bakerian Lecture in 1917 under the title " The Configurations of Rotating Compressible Masses " (published in *Phil. Trans.* A, **218**). He was awarded the Royal Medal of the Royal Society in 1919, in which year he became one of the Honorary Secretaries of that Society, serving until 1929. During his Secretaryship he developed the Society's *Proceedings A* into a leading scientific journal from a status of comparative unimportance.

He was created a knight in 1928. In 1934 he was President of the British Association at its Aberdeen meeting. He became an Honorary Fellow of the Institute of Physics in 1929. He was awarded the Franklin Medal in 1931, the Mukerjee Medal of the Indian Association for the Advancement of Science in 1937, and the Calcutta Medal of the Royal Asiatic Society of Bengal in 1938. He received Honorary degrees from Oxford, Manchester, Dublin, Aberdeen, St. Andrews, Johns Hopkins, Benares and Calcutta. He was awarded the supreme distinction of the Order of Merit in 1939.

Jeans married in 1907 Charlotte Tiffany, daughter of Alfred Mitchell, of New London, Connecticut. She died in 1934, leaving one daughter. In 1935 he married Susi, daughter of Oskar Hock, of Vienna, by whom he had two sons and a daughter. He died at his home, Cleveland Lodge, Dorking, on 1946 September 16.

Jeans was brisk, matter-of-fact and business-like in ordinary conversation, not at all suggesting the deep academic thinker and mathematician that he was. In lecturing this style of his developed into a most attractive persuasiveness. He was also deeply interested in music, and possessed and played his own organ. Mention may be made here of his semi-popular and highly successful book *Science and Music*, published in 1938, in which his treatment ranged from " Tuning Forks and Pure Tones " through " Harmony and Discord " to the acoustics of the concert room.

The Order of Merit was a public recognition of the fact that Jeans attained the highest possible distinction both in scientific research and in the dissemination of the results of scientific research amongst the community at large. Primarily Jeans was a mathematician—an applied mathematician, if we use the term in its sense of natural philosopher—who devoted his gifts to elucidating problems in theoretical physics on the one hand and in astronomy and cosmogony on the other hand.

His earliest and his latest original papers were concerned with the evolution of celestial bodies, especially the stability of masses of fluid with or without rotation. But

there was a phase when his interests were directed chiefly to statistical mechanics, in relation both to matter (molecules and gas theory) and radiation (quantum theory). After this he returned to his first love, and extended his interests to include stellar dynamics and the motions of and in star-clusters, the origin of stellar energy, the equilibrium of gaseous and liquid stars and planetary nebulae, the evolutionary history of star-types and spiral nebulae, the origin of stellar variability and the phenomenon of radiative viscosity. On all these topics he wrote with amazing fluency, in a highly readable mathematical style. He was master of his mathematical techniques, which he never allowed to overwhelm his physical objectives, and it is fair to say that he scarcely wrote a dull page. Indeed it is difficult to describe the under-current of thrilling expectation which Jeans's technical papers and treatises conveyed to the interested reader. The present writer vividly remembers being almost swept off his feet when he first read the passages in Jeans's *Dynamical Theory of Gases* dealing with systems of N molecules described in 6N-dimensional phase-space (this was in 1919, before he knew Jeans personally); it was an emotional experience seldom equalled in the writer's mathematical experience. Power and generality—those were the features of Jeans's mathematical style at its best. He always *led* the mathematics, never allowing it to dominate. For sheer beauty of technical exposition Jeans must rarely have been surpassed.

But, almost suddenly, this phase of scientific creative work gave place to a phase of popularization. His last technical paper, on "liquid stars", in the *Monthly Notices*, appeared in 1928; his popular *The Universe Around Us* appeared in 1929, and thereafter he devoted himself to the writing of books in which he expounded, for world-wide audiences, the results of his own and others' researches in the fields he had made his own. These volumes were distinguished by a fertility of simile which made real to his readers both the incredibly small dimensions of atomic physics and the incredibly large dimensions of cosmical physics. He had a happy way of hitting off orders of magnitude so that they could be readily apprehended. This was no mere pose—he was possessed of a power of mental arithmetic, of rapidly estimating the sizes of physical quantities, which was amazing; and he could perform as readily in a public lecture or in ordinary conversation as in the privacy of his study. The writer remembers his rapidly estimating the cubic capacity of wood in the giant pines of California, and correcting someone present who disagreed with the answer. It is true that Jeans sometimes bludgeoned the minds of his readers with the vastness of astronomical distances or masses, and had a tendency to over-positiveness in his recapitulations of not fully accepted theories. But his popular writings were as enjoyable, as pellucid, as exciting as his technical papers; and astronomy owes a debt to Jeans for the remarkable public interest in what is sometimes reckoned, in this sadly utilitarian age, a mere academic and economically useless study.

I pass to an account of the substance of his original work. Jeans's earliest memoirs were in the *Philosophical Transactions* of the Royal Society, and closely followed paths trodden by Sir George Darwin. These early results were amalgamated, digested and extended in his Adams Prize Essay of 1917, which is considered below. Jeans soon turned to physics. It was soon after the turn of the century; Lord Rayleigh had attacked the problem of the partition of radiant energy in an enclosure, on the classical theory, and Planck had enunciated his radiation law. Jeans developed new proofs of the theorem of equipartition of energy amongst the degrees of freedom of a system describable by a large number of coordinates, and applied them both to molecules and to radiation. The result was to confirm and render more precise the result enunciated

by Lord Rayleigh, which has since been known as the Rayleigh-Jeans law:—the classical partition of radiant energy (of wave-length λ), per unit volume, in an enclosure at temperature T, is $8\pi RT\lambda^{-4}d\lambda$. This was an essential step in the proof of the inadequacy of classical mechanics, for it indicated, in contradiction to observation, that the energy of black radiation should be concentrated in the smallest wave-lengths.

Jeans summarized his researches, and expounded the whole of the kinetic theory of gases in his fine treatise, *The Dynamical Theory of Gases* (first published in 1904); it has appeared in many later editions, and, like its companion volume *The Mathematical Theory of Electricity and Magnetism* (first published in 1908) has been used by generations of students. In 1914 there appeared Jeans's *Report on Radiation and the Quantum Theory*, written for the Physical Society of London, which had a marked influence in leading to the general acceptance of the Quantum Theory.

Jeans did not become a Fellow of the Royal Astronomical Society till 1909, and did not publish in its *Monthly Notices* until 1913. Thereafter he published some thirty-five substantial papers and notes in the *Monthly Notices*, the series ending in 1928. As time went on, his ideas developed and his conclusions were revised. His considered conclusions were published in the superb *Problems of Cosmogony and Stellar Dynamics* (the Adams Prize Essay), published in 1919, and in *Astronomy and Cosmogony* (1928). In view of these volumes it is scarcely necessary to describe the individual technical papers in *Monthly Notices*. It may be mentioned, however, that Jeans's earliest papers in *Monthly Notices* dealt with star-streaming, the motions of star clusters and the structure of the galaxy. This work was very fine. It has formed a basis for recent developments by Chandrasekhar, Camm and others. Jeans was a pioneer in the domain of modifying the methods of the dynamical theory of gases so as to make them applicable to a collection of stars, in which close encounters are rare but the cumulative effect of small deflections is appreciable.

Jeans's researches on the stability of rotating masses of fluid were fully expounded in the *Problems of Cosmogony and Stellar Dynamics*, which is difficult to over-praise. When a mass of incompressible liquid is rotating under its own gravitation with constant angular momentum but increasing density, it first passes through a stable series of equilibrium configurations known as Maclaurin's spheroids; these remain secularly stable until $\omega^2/2\pi\gamma\rho$ reaches the value 0·18712; thereafter, stability passes to a second series, known as Jacobi's ellipsoids; at $\omega^2/2\pi\gamma\rho = 0{\cdot}14200$ a new configuration of equilibrium becomes possible, called by Darwin the " pear-shaped " figure, which is produced by the formation of a furrow round the long axis of the Jacobian ellipsoid. This pear-shaped figure was discovered by Poincaré in 1885. Important cosmogonic questions are involved in the stability or instability of the pear-shaped figure. If it is stable, it might be expected to evolve quasi-statically by deepening of the furrow, into two separate bodies, forming a stable double-star configuration; but if it is unstable, increasing density along the Jacobian series should result in a cataclysm, and we should have a possible cataclysmic origin for double stars. Poincaré was unable to ascertain definitely the stability of the pear-shaped figure, though it was Poincaré who developed the general principles governing stability in a famous paper in the *Acta Mathematica* of 1885. In 1902, Sir George Darwin published in the *Philosophical Transactions* of the Royal Society a lengthy investigation in which he claimed to show that the pear-shaped figure was *stable*; but in 1905 Liapounoff published at St. Petersburg, in Russian, an investigation claiming to show that the pear-shaped figure was *unstable*. It was difficult to judge who was right. Jeans re-attacked the question by calculating the

gravitational potential of a distorted ellipsoid by a new and powerful method, avoiding the method of ellipsoidal harmonics used by Darwin, and finally showed that the pear-shaped figure was unstable. Moreover he was able to show how Darwin had gone astray, not so much by an actual error as by an unexpected complexity in the relation of the pear-shaped figures to the Jacobian ellipsoids.

Jeans reproduced the whole of his investigations very elegantly in his *Problems of Cosmogony* of 1919. But in that volume he did much more than summarize his own investigations. He gave a general account of Poincare's theory of linear series and points of bifurcation, considered separately the pure rotation problem, the tidal problem and the double-star problem, both for incompressible and compressible matter, treated of Roche's model, reproduced the calculation of Roche's limit for satellites, and fused the whole subject into a monumental unity. He then, with this substantial mathematical harvest as a background, applied the results to see what light they shed on the origins of the different types of celestial bodies. He concluded that double stars could be formed by the cataclysmic fission of " liquid " masses consequent on increasing density; that large compressible masses of the type of Roche's model would break up by forming a sharp lenticular ledge, which with increasing contraction of the main mass would eject streams of matter from two antipodal points determined by the residual tidal force arising from the rest of the universe, and that this might be the origin of the spiral nebulae; but that rotation alone could never bring into being anything resembling the solar system. He accordingly rejected the nebular hypothesis of Kant and Laplace in its original form, and favoured instead a disruption of the Sun by the tidal effects of a passing star, as suggested in a less precise form by Chamberlin and Moulton. He emphasized the rarity of encounters of the necessary closeness (in the then state of knowledge) and concluded that the solar system might even be unique in the universe.

Many of Jeans's specific applications of his results need or have found revision in the light of our later knowledge, and especially in the light of the expansion of the universe. Nevertheless, *Problems of Cosmogony* was a magnificent attack on magnificent problems, conducted by a master-mathematician. The cores of its investigations remain standard work to-day. And it must be remembered that Jeans repeatedly emphasized in this book the provisional nature of his applications. Similar reservations, combined with flashes of foresight, occur in many of his papers. Thus, as early as 1916, when he was discussing the density-law in star-clusters and reducing the problem to an Emden equation, he wrote: " It is as though a rich pattern were being woven, and we had only been able to follow one thread " (*M.N.*, **76,** 567, 1916). In 1922 he foresaw the likelihood of the expansion of the universe when he remarked that " many circumstances . . . . . suggest that the stars of our system must have been more closely packed than they now are " (*M.N.*, **82,** 139, 1922). And again, in 1927, before the doctrine of the creation of the universe at the natural origin of time had been developed, he remarked that " it would be difficult to deny that all the matter of the universe may have been created at the same instant " (*M.N.*, **87,** 709, 1927).

Jeans's later book, *Astronomy and Cosmogony*, which combined into a single volume much of the Adams Prize Essay together with his own researches from 1917 to 1928 on the subject of stellar equilibrium and stability, was perhaps less successful. It exhibits the same grand sweep of investigation, the same width and power, but less clarity. And it has to be confessed that many of his results are not accepted to-day, at any rate in the form in which he put them forward. He dealt with stellar equilibrium in a different manner from Eddington. He claimed to show that the cores of stars would be unstable

if they were wholly gaseous, and that, if the equation of state of stellar matter is taken to be of the form $p_G \propto T^{1+s}$, we must have $s>0$ as a necessary condition of stability. He did this by an actual calculation of the equation for the oscillations of such a star. He described this result by saying that the interiors of stars must be "liquid". (The view of many workers to-day is that the stars have a convective, not radiative, core.) He then claimed to show that the untenanted portions of the Russell-Hertzsprung diagram corresponded to regions of instability due to successive removals of shells of electrons by ionization; thus the giant stars were to correspond to the loss of the M-ring electrons, the main sequence to the loss of L-ring electrons and the white dwarfs to the loss of K-ring electrons, these being stable halting-places where the configurations of equilibrium would tend to congregate. He was mistaken in some of his conclusions: for example he thought that the central temperatures of white dwarfs must be enormously high, whereas to-day we recognize that it is only in the non-degenerate fringe of a white dwarf that an appreciable temperature gradient can be present. He required further that the atoms forming the interiors of stars should have atomic numbers of the order of 95, that is to say, above 92 (uranium), the then highest known atomic number. Lastly he attributed Cepheid variation to the rotations of ellipsoidal stars near the verge of instability, as against the current pulsation theory.

Though these conclusions were far from fashionable when they were first announced, it is possible that time will justify Jeans. Certainly there is much less acceptance to-day of what was in 1928 the "orthodox" theory of stellar equilibrium. But it should be remembered that Jeans made several valuable suggestions in the early days of Eddington's theory of the radiative equilibrium of the stars. In 1917 he pointed out that, at the temperatures deduced by Eddington for stellar interiors, the atoms must be very considerably ionized, and the mean molecular weight much lower than Eddington had originally taken; and Eddington adopted this suggestion. Years before that, in 1904 in fact, Jeans had suggested as a possible source of stellar energy the mutual annihilation of electrons and what are now called protons, with conversion of mass into energy.

Yet it would be improper to minimize the fact that those two Titans, Eddington and Jeans, differed and differed strongly on the theory of stellar structure. Eddington's theory had a beauty, the beauty of a rosy dawn, in bringing together in a very simple way the ideas of perfect gases, of radiation-pressure and ionization, of opacity, of hydrostatic and radiative equilibrium. And Eddington, the professional astronomer, dealt with the physical properties of matter in a more physical way than Jeans, the physicist, was accustomed to do. Nevertheless, in the present writer's opinion, Jeans was fully justified in his criticisms of the early forms of Eddington's theory. Eddington was led to the conclusion that a star was built according to an Emden polytrope of index $n=3$, and he thus appeared to be able to show, without any consideration of the mechanism of energy-generation, that an arbitrary mass of perfect gas, in a steady state, must have a perfectly definite luminosity, whereas, as Jeans pointed out, an arbitrary mass of matter could be in a steady state with any luminosity whatever, depending on the intensity of the energy-sources with which it was provided. Eddington never explicitly recognized that his original luminosity formula was merely the *mathematical* condition that a given mass of gas should be gaseous throughout; it did *not* predict that a star of this mass should have this particular luminosity. For his model was open to the obvious objection: what happened if its natural sources of energy did not amount to the prescribed luminosity? The answer is now well known: the star ceases to be wholly in the state of a perfect gas, and assumes a composite configuration; Emden's equation has other

solutions besides that used by Eddington, and it is these other solutions which are relevant to the gaseous part of the star when the total rate of generation of energy does not equal that predicted by the luminosity formula. (The white dwarfs are examples.) Jeans was as much puzzled as the astronomical world in general by the way Eddington appeared to be producing rabbits out of a hat: it was obviously impossible to find out the luminosity of a star without consideration of the mode of generation of stellar energy. But Jeans never clinched his argument in the way I have described above. The answer to Eddington's contentions was to express the different stellar variables—central temperature, pressure and density, radius and effective temperature—as functions of *two independent variables*, L and M. And this Jeans never did. For example he explicitly stated, on p. 83 of *Astronomy and Cosmogony*, that a star of given mass M can have any luminosity whatever from 0 to ∞ (actually there must be an upper limit, for equilibrium); but yet he was so little able to emancipate himself from Eddington's ideas that on p. 88 of the same work he stated that the ratio of gas-pressure to radiation-pressure for stars of different (small) mass M is proportional to $1/M^2$, not recognizing that if L is arbitrary the ratio in question can take arbitrary values.

In *Astronomy and Cosmogony* Jeans appears less of a physicist than his admittedly important contributions to physics would have led us to expect. He scarcely formulated the problem of stellar structure with the clarity with which he stated the stability problems in the Adams Prize Essay. For example, he used the Saha dissociation formula (as modified by R. H. Fowler) in contexts where he was specifically assuming the material not to be in the form of a perfect gas, but to be akin to a liquid, whereas the derivation of the dissociation formula uses the entropy-formula for perfect gases. Nevertheless, the striking series of papers in *Monthly Notices*, of which *Astronomy and Cosmogony* was an expansion, includes several topics which were characteristic of Jeans at his best. He studied the equilibrium of the shell of a planetary nebula; he examined the effects of loss of mass on the dynamics of binaries; and he discovered, and traced the astronomical consequences of, the phenomenon of radiative viscosity. And so *Astronomy and Cosmogony*, irritating though it is in many parts, was a notable contribution to the theoretical problems of stellar structure. It compels attention throughout. It showed the subject in a state of flux and transition; and it demonstrated Jeans's courage in venturing on conclusions differing in so many ways from those of his brother theorists.

Having made up his mind about the main cosmogonic questions, Jeans set himself to convey his results to the public at large. His principal popular volumes, in addition to the one on music already mentioned, were *The Universe Around Us* (1929), *Eos or the Wider Aspects of Cosmogony* (1930), *The Stars in Their Courses* (1931), *The New Background of Science* (1933), *Through Space and Time* (1934) and, in a different vein, *The Mysterious Universe* (1930) and *Physics and Philosophy* (1942). In all these he gave to his readers that enjoyment of what he called "the most poetical of the sciences" which he had experienced himself and which he had previously shared with his scientific colleagues.

Jeans was always much impressed by the Second Law of Thermodynamics. He had dealt with it in refined detail in his work on gas-theory, on Boltzmann's H-theorem and on statistical mechanics generally; and he preached without reservation the doctrine of the ultimate heat-death of the universe. I think he tended to ignore the facts (*a*) that the formal thermodynamic proof of the increasing property of entropy is subject to severe limitations; (*b*) that the phenomenon of the expanding universe, with its indication of a natural origin of time and with the slowing down of time at great distances owing

to the recession, causes a substantial revision of the heat-death doctrine. This was an example of Jeans's tendency to take an over-positive, non-critical, non-sceptical view of contemporary *physics* (*The New Background of Science* is altogether too complacent), although that was not his attitude to astrophysics. It was also an example of Jeans's tendency to move off into the philosophical implications of science. Like Eddington he attached importance of a philosophical kind to the principle of indeterminacy, suspecting that many causal laws were actually statistical in their origin; in this he was no doubt influenced by his early researches in statistical mechanics. But what impressed him most in Nature was its apparent docility to the sway of *mathematical* concepts. Emphasizing that mankind had successively rejected the anthropomorphic view of the universe, and the engineering view of the universe customary in the nineteenth century, he considered that the world appeared to be built on what could only be described as a mathematical pattern; in short, that the Great Architect of the universe must be a mathematician—that " the universe can best be pictured as consisting of pure thought, the thought of what we must describe as a mathematical thinker ". " Primitive cosmologies pictured a creator working in space and time, forging sun, moon and stars out of existent raw material. Modern scientific theory compels us to think of the creator as working outside time and space, which are part of his creation, just as the artist is outside his canvas ". And Jeans could quote Plato as holding the same ideas.

Jeans was much criticized by professional philosophers; but in *Physics and Philosophy* he gave as good as he got, and made some shrewd hits against traditional philosophy, accusing it of omitting all half shades in its picture of reality and attributing its differences from physics to differences of idiom. I think it is a sign of Jeans's greatness that he ended as a philosopher; that he came inevitably to philosophy by the path of mathematics and physics; that he was not content to contemplate the universe merely as a spectacle, but that he had to seek the inner meaning of it all. Jeans died rich in honours; but to him the greatest honour was that in all his activities he deserved well of astronomy. He was elected a Fellow on 1909 May 14.

E. A. MILNE.

SHUNICHI KAWASAKI was born on 1896 January 24, at Shimo-Toyama near Kusatsu-Machi Shiga-Prefecture, Japan, as the first son of Kiyoshi Kawasaki. After being educated at a local primary school and the Second Middle School of Kyoto, he entered the Higher Normal School of Hiroshima in 1913, from which he graduated in 1917 and spent two years in teaching at the Normal School of Hyogo-Prefecture. In 1919 he entered Kyoto Imperial University where he studied physics and astronomy. In March 1922 he graduated from the University, and in May he was appointed an astronomer at the International Latitude Observatory of Mizusawa where he continued the service for over twenty years. In 1940 he became a member of the National Committee of the National Research Council and in 1941 a member of this council. He also became a member of the Committee of the Imperial Japanese Geodetic Commission in 1941. In the same year he succeeded Professor H. Kimura as Director of the Observatory. He was unusually healthy ever since his early years, so that, when he was seized with an illness in the spring of 1942, his colleagues and friends were quite surprised. Later his health and strength showed an inclination to recover, but towards the year's end he caught pneumonia and died on 1943 January 19.

In his undergraduate course at Kyoto Imperial University, Kawasaki was absorbed in the problem of double stars; at Mizusawa, however, he spent his whole time on latitude variation. He examined the behaviour of the zenith telescope, and the effects caused probably by meteorological elements. His interest in the details of observer's personal equation are to be mentioned. He studied also with interest the effect of the Moon's position in latitude and longitude observation.

In 1932 Kawasaki was sent abroad, and stayed mainly at Greenwich, where he carried out special studies on the variation of that latitude by the courtesy of Sir Frank Dyson, the then Astronomer Royal.

Kawasaki returned home in 1934, after visiting several observatories in Europe and America and also attending the Lisbon Meeting of the International Union of Geodesy and Geophysics in 1933. He was convinced of the important rôle of meteorological elements on the observed latitude and was planning to carry out a thorough study of the problem by means of the newly mounted Cookson Floating Zenith Telescope. This observation was begun in 1940 January and has been continued until now.

In 1936 he received an award at the Okayama Meeting of the Japanese Association for the Advancement of Science, and in 1937 he obtained the degree of Doctor of Science from the Kyoto Imperial University for the study under the title " On Minor Variation of Latitude at Greenwich ".

Kawasaki was married to Miss Joko Obara, in 1922, who died in 1940, and remarried to Miss Yukiko Asano in 1941. She and three sons and a daughter survive him and they are now living in his native village.

Kawasaki was of a gentle and amiable disposition, which was probably inherited from his father. He was especially sympathetic to the professional careers of the members of his staff at Mizusawa. He was extremely conscientious in his own work and of the utmost sincerity in his scientific career, paying every attention to the details of daily routine in computation and in observation, so that his results of researches were generally appreciated as being most reliable and dependable.

Kawasaki's taste was many-sided. Although he was usually not very talkative he was an excellent essayist, and his writings were frequently enjoyed by friends. He composed good pieces of Tanka (Japanese Short Poems) in his leisure hours. Everybody he knew loved him so that his loss was mourned deeply among a wide circle of official as well as personal connections.

Kawasaki was elected a Fellow of the Society on 1933 May 12.

Y. HAGIHARA.

ADRIAN VAN MAANEN was born 1884 March 31, in Sneek, Holland. He took his academic training at the University of Utrecht, receiving his doctor's degree in 1911. During his graduate study he was fortunate in being allowed to spend some of his time at the Groningen Astronomical Laboratory where he came in contact with Professor J. C. Kapteyn, who thereafter became the guiding spirit in his life. The problems of stellar motions and distances, which Kapteyn had so masterfully developed, immediately attracted his unfailing interest.

From 1908 until 1913 Kapteyn, at the invitation of Dr George E. Hale, paid an annual visit to Pasadena and Mount Wilson as an Associate of the Carnegie Institution of Washington. It was natural, then, that his young protégé from Utrecht should be attracted by the astronomical opportunities in America. Accordingly, he came to the

Yerkes Observatory as a volunteer assistant in 1911 and spent a year there measuring the proper motions of stars in and around the Orion nebula.

In the summer of 1912, van Maanen came to Mount Wilson as a visitor and on September 1 was given an appointment to the staff of the Observatory. For two years he took part in the solar observations and the programme of stellar spectroscopy. He also began the exceedingly difficult task of measuring the minute Zeeman displacements of the solar spectral lines which might be affected by a general magnetic field in the Sun. These arduous measures were continued for several years and are the chief basis for a positive conclusion as to the presence of such a magnetic field.

In 1914 the equipment at the 80-foot Cassegrain focus of the 60-inch telescope for taking direct photographs was completed and a programme of proper motion and parallax determination was carried on by van Maanen single-handed for more than 30 years. His 500th parallax determination was completed in 1945. This number of stellar distances is greater than that of all that were known at the time he began his work. In these observations involving the most accurate positions from astronomical photographs, a reflecting telescope was used for the first time and it took courage to go ahead with the project in the face of much doubt and criticism. Van Maanen was able to prove that, with due care, sufficiently reliable parallaxes could be determined by such instruments and in 1920 a similar programme for the fainter stars was inaugurated at the Newtonian focus of the 100-inch reflector.

For measuring the pairs of parallax plates, he introduced the use of the stereocomparator which he had tried at the Yerkes Observatory for the Orion stars. He found that it was readily adapted to parallax measures and that the process of measurement and reduction was somewhat simplified in this way.

From 1914 until 1923, in addition to his parallax programme, he spent a great amount of time and effort in an attempt to measure the internal motions in spiral nebulae by comparing plates taken at epochs from 5 to 15 years apart. Although the material was not homogeneous, some of the plates being taken at the Cassegrain focus, some at the Newtonian, and some even with other instruments, the results were strangely accordant in showing a rotation period of the order of 100,000 years or, perhaps, a motion outward along the arms of the spirals. Slow as this motion is, it is much too rapid to be admitted with our present knowledge of the distances of these extragalactic bodies. The fact seems to be that the time-intervals between the pairs of plates were too short and the observational material inadequate to cope with the difficulties of the problem. For the present, at least, we shall have to rely on spectroscopic results for our picture of the motions in the spiral nebulae.

Van Maanen was greatly interested in the distribution of stars in the neighbourhood of the Sun. Since this part of space is the only region where we may observe stars of extremely low intrinsic luminosity, he turned his attention more and more as the years passed by to the stars of the lowest absolute magnitude. Measures of distances and luminosity were made. By plotting the numbers of large proper-motion stars of different absolute magnitude he found a maximum at visual absolute magnitude 10·3 and thus reached the important conclusion that we may not hope to find an indefinite number of stars of extremely low luminosity.

During his 33 years at the Mount Wilson Observatory van Maanen contributed 150 scientific papers. The more important results on proper motion and parallax were described in about 50 contributions. Many other papers are notes on individual stars and articles for the Dutch journals and societies in which he kept up his interest.

Van Maanen's Fellowship of the Royal Astronomical Society dated from 1915. He was a member of many other societies, including the American Astronomical Society, Astronomical Society of the Pacific, Royal Astronomical Society of Canada, Société Astronomique de France, Astronomische Gesellschaft, International Astronomical Union, and a number of Dutch scientific societies, including the Amsterdam Academy; and he enjoyed attending scientific meetings where he could meet and discuss matters of common interest with a wide circle of friends.

Dr van Maanen is survived by two sisters and a brother in Holland.

A. H. JOY.

(Adapted, by courtesy of the editor, from *Popular Astronomy*.)

HENRY CROZIER PLUMMER, President of the Society from 1939 to 1941, died at Oxford on 1946 September 30 within a few weeks of his seventy-first birthday.

Plummer was born at Oxford on 1875 October 24, the eldest son of W. E. Plummer, then first assistant at the University Observatory (he was appointed when the Observatory was established in 1873) and subsequently Director of the Observatory of the Mersey Docks and Harbour Board and Honorary Reader in Astronomy in the University of Liverpool. He was educated at St. Edward's School, Oxford and Hertford College, where his distinctions included Firsts in Mathematical Moderations and Final Schools, and the Open Mathematical Scholarship. After studying physics for a year Plummer went to Owen's College, Manchester in 1899 as Lecturer in Mathematics, returning to Oxford after a year as Demonstrator in the Clarendon Laboratory ; a year later he was appointed assistant in the University Observatory, of which H. H. Turner was then Director; there he remained until 1912, except for a year's sojourn at Mount Hamilton as Fellow of the Lick Observatory. As a young and ambitious astronomer Plummer early realized the immense potentialities of spectroscopy, and his year's stay in America gave him the much-prized opportunity of making himself conversant with the large-scale developments then proceeding rapidly in the great American Observatories. In 1912 he succeeded Sir Edmund Whittaker as Andrews Professor of Astronomy at Trinity College, Dublin and Royal Astronomer of Ireland. At Dunsink Observatory Plummer found an institution that had, on the whole, passed its meridian as regards effective practical work; the many natural advantages of Dunsink as a place of residence could not compensate a young and eager astronomer for the almost certain prospect of having to make the best of the existing equipment without any hope of acquiring instruments of such power and variety as the contemporary state of astronomy required. The political troubles in Ireland during and immediately after the first world war made things unpleasant for Plummer who, by nature, was gentle and retiring and opposed to violence in any shape or form; circumstances thus forced him into an almost monastic seclusion from which he was glad to escape when, in 1921, a vacancy occurred in the Professorship of Mathematics at the Military College of Science at Woolwich. Here Plummer found a congenial sphere of scientific activity till his retirement in 1940; he returned to Oxford where he lived until his death in 1946. In 1924 he had married Beatrice, daughter of H. H. Howard, M.R.C.S.; their kindliness and gracious hospitality during the war years are remembered with gratitude by many of Plummer's astronomical colleagues. Mrs Plummer died in the early spring of 1946, a blow which prostrated Plummer and from which he never recovered; there were no children of the marriage.

Plummer's astronomical researches covered a very wide field, and there was hardly a department which did not excite his interest and stimulate him to make some further advance. In his early days at the Oxford Observatory the current work on the Astrographic Catalogue claimed a great deal of his attention, and he made a meticulous study of the many problems, mathematical and practical, inherent in the reduction of photographic plates ; at the time there was a great deal of controversy on such matters, but Plummer's mathematical ability, his knowledge of the capacity of any instrument for the job in hand and his almost uncanny skill in the theory of errors overcame all criticism. It may be added that Plummer found a peculiar satisfaction in these investigations, for his father when at Oxford had been responsible for much experimental work and preparation for the Oxford share of the enterprise in addition to representing Pritchard (the first Director) at the Paris Astrographic Conference of 1891.

In his early years at Oxford, too, he made his first investigations in planetary theory, mainly on " oscillating satellites "; as is well known there are five exact solutions of the problem of these bodies in each of which the bodies preserve a constant configuration which revolves with uniform angular velocity; if one of the bodies is of negligible mass and is slightly displaced from its position of relative equilibrium, it describes a periodic orbit with reference to the equilibrium point (the body is then called an " oscillating satellite "). Plummer's work in this field was stimulated by the investigations of Darwin and Charlier; it may be added that he returned to this subject in 1932 in a paper suggested by the extensive numerical investigations then being carried out at Copenhagen Observatory. In these early years Plummer wrote on such diverse subjects as occultations, the application of projective geometry to the determination of binary-star orbits, the accuracy of eye-observations of meteors and the determination of radiant points, the possible effect of radiation on the motion of comets, the theory of aberration and the principle of relativity. He was always very much interested in the geometry of instruments and his last address in 1941 as President of the Society dealt with the development of the vertical telescope, a subject to which he had made notable contributions in the first decade of the century; some of his suggestions found practical expression in the tower telescope at Mount Wilson.

In 1911 Plummer contributed a valuable paper on the problem of the distribution of stars in globular clusters, in which he devised elegant mathematical formulae giving the relation between the space-distribution of the cluster-stars and their two-dimensional distribution on photographs. About this time he began a long series of investigations on the parallaxes of stars mainly of types B and A; starting from the assumption that these stars (in or near the galactic equator) have no component perpendicular to the galactic equatorial plane—or, alternatively, that the velocity, relative to the Sun, of any star perpendicular to the galactic plane is equal to the parallactic velocity in this direction—Plummer derived a simple formula from which the parallax of a star could easily be calculated from the known values of the proper motion and radial velocity.

At Dunsink, Plummer and his assistant, C. Martin, began an extensive programme on the photographic photometry of short-period variable stars with the 15-inch telescope of the Observatory; the light curves were subjected, in each case, to periodic analysis. Although this work has been superseded by more recent observations of superior accuracy—Plummer's estimate of the probable error of a single magnitude determination was $\pm 0{\cdot}03$— it led him to one important conclusion, namely, that such variables cannot be spectroscopic binaries, as the variability of their radial velocity measures seemed at first to suggest, but that the periodic changes in radial velocity could plausibly be

ascribed to radial pulsations in the atmospheres of the stars. This hint of a new physical class of stars was first made in 1913, and developed in subsequent papers; later, Shapley's investigations supported Plummer's suggestion. The pulsation-theory of Cepheids was now fully launched and it soon gave Eddington full scope for a searching mathematical analysis.

Plummer wrote many additional papers at Dunsink on such topics as the velocity of light and Doppler's principle, a further investigation on the distribution of stars in globular clusters, statistics of minor planets, bright meteors, general precession, the ellipticities of the Maclaurin ellipsoids, stationary radiants, multiple solutions in the determination of orbits.

In 1932 Plummer contributed an illuminating paper on the nature of " dependences " in the reduction of astrographic plates; " dependences " had been introduced by Schlesinger some time previously, and Plummer's elegant analytical treatment was an important contribution to this new method of photographic astrometry. In 1937 there appeared a paper on the masses in single-spectrum binary systems, written by Plummer on the text—taken from Dr Aitken's book " The Binary Stars "—that " the value of the mass-function is frequently omitted by the computer of orbits, for it gives very little definite information ". Referring to this statement Plummer remarks at the beginning of his paper: " This is a hard saying, for it implies that from all the work spent in deriving orbits of single-spectrum stars no information bearing on the masses of the systems can be deduced ". Plummer's line of attack in deriving the mass-ratio of such systems was to recognize that the mass-function may be regarded as a function of $m \sin^3 i$ and the mass-ratio m_1/m, the value of the former for any class being taken from the statistics of the corresponding double-spectrum systems. The method is applied to all single-spectrum systems in considerable detail.

During his period (1939–41) as President of the Society Plummer gave the addresses on the awards of the Society's Gold Medal to M. Lyot (1939) and Dr E. P. Hubble (1940) and a third address in 1941 on the development of the vertical telescope already alluded to.

Plummer's interest in celestial mechanics led to the publication of his most important book *Dynamical Astronomy* in 1918, a notable contribution to the subject; here he revealed very conspicuously a freshness of outlook and an elegance in mathematical presentation so long familiar in his papers. His *Principles of Mechanics* appeared in 1929; his great knowledge of the " theory of errors " found expression in *Probability and Frequency* published in 1939.

Plummer was keenly interested in the history of science and when, in 1939, the Royal Society appointed a committee to advise on the publication of Newton's works and letters he willingly undertook the difficult task of editor. Unfortunately, it was found impossible under war conditions to have anything published in time for the tercentenary in 1943 of Newton's birth; this great enterprise when completed will owe an enormous debt to Plummer's self-denying labours in the earlier war years when his strength was still unabated. At the Society's triple centenary celebrations on 1942 October 9, at which Galileo, Newton and Halley were commemorated, the address on Newton was given by Plummer. He was Halley Lecturer at Oxford in 1942, the subject of his address—notable for the extent of historical research which it reveals—being " Halley's Comet and its Importance ".

In disposition Plummer was modest and reserved, with an unsuspected sense of humour. To those who had gained his confidence he was a staunch friend and loyal colleague. Elected a Fellow of the Society on 1899 December 8, he served on the Council

in 1915 and from 1935 to 1942; he was a Vice-President in 1936–1937 and again in the year following his Presidency during the first two of the difficult war years. He was elected to the Royal Society in 1920.

W. M. SMART.

VIOLET FLORENCE WHITE was born in Clapham Park, London, in 1906 and died at Wanstead on 1946 September 15. She was educated privately until she was ten, when she went to the Mundella Secondary School, Nottingham, and thence to Clapham County Secondary School for six years. She there gained a State Scholarship to Bedford College, which she joined in 1925 October. In 1928 she obtained a First Class degree in Mathematics and was awarded the University Gilchrist Studentship, enabling her to study dynamics and celestial mechanics with Dr Marshall. In 1930 she obtained the M.Sc. with a mark of distinction, and started work at the University of London Observatory, as a part-time postgraduate student, in the autumn term of 1930. She took a number of photographs with the 24-inch reflecting telescope, measured and reduced the plates, and contributed a number of papers to the Society on the proper motion of faint stars in the nebula fields originally photographed by Dr W. E. Wilson, F.R.S., at Daramona, Ireland.

In 1931 she was Research Assistant for a year at the Imperial College of Science and Technology, when she returned to Bedford College, and in 1935 she took up the post of assistant lecturer in mathematics at Westfield College until 1937. She then became lecturer in Mathematics at West Ham Municipal College and later at S.E. Essex Technical College.

Miss White was a keen and enthusiastic teacher in both school and University, but her real love was Astronomy, and I believe she always regretted that fortune did not allow her to make this her career. With many enthusiasms and activities, Miss White was an ardent feminist and keen motorist. She was elected a Fellow of the Society on 1930 May 9.

C. C. L. GREGORY.

JAN WOLTJER, Jr., was born in Amsterdam on 1891 August 3. He died at Leiden on 1946 January 28, a victim of the starvation in the Netherlands during the winter 1944–45, which had permanently undermined his health.

He studied at the Universities at Amsterdam and Leiden. At the latter institution he specialized in theoretical astronomy and prepared a doctor's dissertation (1918) on the theory of the motion of Hyperion, one of Saturn's satellites. In 1919 he was appointed lecturer in astronomy at the University of Leiden. He held this post until his death. He had been connected with the Leiden Observatory since 1913, first as observer, since 1920 as "conservator". He is remembered as a gifted teacher by the many younger Dutch astronomers who studied there since 1919.

The motion of Hyperion was his principal research topic until 1928 when the finished theory and discussion of observations appeared in the Annals of the Leiden Observatory. Shorter studies by him on resonance problems in the solar system were published during this period in the *Bulletin of the Astronomical Institute of the Netherlands*. About 1925 he changed his principal field of specialization from celestial mechanics to theoretical astrophysics. The rapid development of the theory of stellar atmospheres and of stellar

interiors had aroused his intensive interest just when he had come to the conclusion that the available methods in celestial mechanics did not fully satisfy his desire for mathematical rigour. How well he had acquainted himself with the new field can be judged from his review of Eddington's book *The Internal Constitution of the Stars* (*Observatory*, **50**, 56, 1927). His earlier astrophysical research dealt primarily with stellar atmospheres and the solar chromosphere. In more recent years the Cepheid pulsation problem became his favourite topic. In these investigations which contain many original and valuable ideas he made extensive use of methods of analysis which were developed originally for the treatment of problems in celestial mechanics.

DIRK BROUWER.

HARRY EDWIN WOOD, Union Astronomer from 1928 to 1941, was born in Manchester on 1881 February 3, and died at Mortimer, Cape Province, on 1946 February 27, a few days after a heart attack. He studied physics at Manchester under Sir Arthur Schuster and obtained his M.Sc. degree with first class honours. Sir Arthur Eddington and J. W. Nicholson were two of his fellow students. Wood stayed at Manchester for some time after his graduation as one of Schuster's assistants, and worked principally on the interference phenomena of light, some of his work being later incorporated into Schuster's classical work on " Optics ".

In 1906 Wood was appointed Chief Assistant at the recently established Transvaal Meteorological Observatory (now the Union Observatory) and spent a short period at the British Meteorological Office to prepare himself for this position. The director of the Transvaal Observatory was R. T. A. Innes and, as might be expected, Innes could not refrain from tackling Astronomy, especially when living under the clear skies of the high veldt. Soon after Wood's arrival at Johannesburg, the Observatory acquired a 9-inch Grubb refractor which was used by Innes for double-star observing and by Wood for systematic observations of Jupiter's satellites, comets, occultations, etc. In 1909, Franklin Adams gave the Observatory his famous star camera and this quickly became Wood's special instrument. He used it steadily for the work for which its short focal length, its large field of good definition and its powerful light grasp rendered it eminently suitable: the completion for the Southern Hemisphere of the set of star charts which Franklin Adams had started several years earlier at the Cape; the preparation of the Union Observatory Charts as a companion work to the Cape Photographic Durchmusterung; observations of Halley's Comet; the systematic observations of minor planets, comets and variable stars. For many years the responsibility of observing the minor planets which came to opposition in southern declinations rested almost entirely on Wood's shoulders. He discovered several of these elusive objects and computed the first orbits for many of them as he did in the case of comets. The names of three of his discoveries commemorate the Transvaal, Pretoria and his native city of Manchester.

Wood was a sound, careful and painstaking observer, conscientiously and systematically carrying out the heavy routine work that fell to his lot. Most of this work was with the Franklin Adams Camera, though he also observed occultations assiduously, and was for many years in charge of the Observatory's seismographs and made a careful study of the earth tremors caused by mining operations on the Witwatersrand. During extended visits to the Cape Observatory he used the Astrographic Refractor to re-photograph much of the Cape's zone of the *Carte du Ciel* in a systematic search for

stars of large proper motion. Mrs Wood, a fellow student at Manchester, shared all his interests and was able to assist him in his work, especially where any drawings or computations had to be made.

In 1914, the Woods took part in the expedition which extended the magnetic survey of South Africa up the Zambesi River to Barotseland. When war came, Wood joined up and served in East Africa, but contracted malaria so badly that he had to be invalided out of the army in 1917. His health never recovered properly from this experience and for many years he suffered from periodic attacks of this undermining sickness. Later, however, these attacks of malaria seemed to become rarer and his health improved considerably.

Wood succeeded Innes as Union Astronomer on 1928 January 1. As Director of the Observatory, Wood did not believe in the heavy hand; he gave his staff the feeling of working with rather than under him and was satisfied when they showed initiative, resourcefulness and enthusiasm. He was an excellently clear lecturer, giving one the impression that he would have been as successful in teaching as in research. His love for the study of plants was such that one felt he might as easily have become a botanist as a physicist or an astronomer; this combined with a love of the free outdoor life of the veldt led to a drastic change at the time of his retirement in 1941.

The Woods sold up their Johannesburg home and moved to Mortimer, a small country village in Cape Province not very far from Cradock. Here they leased a farm and the astronomer became a farmer. The farm was all but self-sufficient, though the man who had until then been in charge of the Union's time-keeping had occasionally to motor into Cradock to compare his watch with the church clock. Though now a farmer, Wood maintained an active interest in the many scientific societies of which he was a member and visited Johannesburg each year to attend the meetings of the $S_2 A_3$ (the South African Association for the Advancement of Science) of which he had for many years been one of the most active members. He also found time to give popular lectures on Astronomy and to prepare several broadcasts for schools.

Wood had a typical English reserve and shyness, coupled with a dry humour which was not always easy to follow at first, until one gradually got to understand it. Though childless, children were attracted to him and he to them. He had an untrained but pleasing baritone voice, and at parties Innes was apt to say: "Let us ask Wood to sing, but give him another glass of wine first". This was supposed to overcome his natural reserve, which might have obstructed the heartiness of his singing.

Wood was a Fellow of the Royal Society of South Africa, an honorary Doctor of Science of the University of the Witwatersrand and a past president of several of the South African learned societies. He was elected a Fellow on 1909 April 7.

R. H. STOY.

PROCEEDINGS OF OBSERVATORIES

Royal Observatory, Greenwich
(*Director, Sir Harold Spencer Jones, F.R.S., Astronomer Royal*)

The purchase by the Admiralty of Herstmonceux Castle, Sussex, with about 372 acres of ground, as a future site for the Royal Observatory has been completed. Consideration has been given to the plans for the removal of the Observatory, together with its instrumental equipment, to the new site. Because of the building difficulties at the present time the removal will be undertaken in stages and will probably extend over several years.

Airy Transit Circle.—The restricted programme of observations with the Airy transit circle is still in operation. During 1946 82 observations of the Sun, 52 of the Moon, 17 of Venus and 30 of other planets were obtained, together with 963 transit and 755 zenith distance observations of stars.

Preparation of the First Greenwich Catalogue of stars for 1950 is still in progress. The proper motions of some 2,100 stars in Part II of the catalogue zone $+0°$ to $+24°$ declination are being derived.

Reversible Transit Circle.—The reconditioning of the instrument for astronomical observations is now in hand. The positions of stars to be used for the determination of time and variation of latitude with the photographic zenith tube at Herstmonceux are to be derived from observations to begin shortly with the reversible transit circle.

During 1946 a considerable amount of observational data was obtained in further investigations of the errors of figure of the pivots.

Another method, designed by Dr Atkinson, utilizing a mirror inserted in the tube has been tried. Unfortunately the tube is not adaptable at present for a satisfactory mounting of the mirror. This method of observation has proved to be free from variable definition of the object, which cannot be eliminated in the normal way when the pivots of the telescope are converted into a collimating telescope, but it has not been possible to eliminate small effects due probably to axial flexure.

So far results show the real pivot errors to be small but the main difficulty is to ascertain from the observed data whether small errors arising from the instrumental equipment used and similar in character to those that would be produced by a slight ellipticity in the figure of the pivots have been entirely eliminated.

Cape Zone Photographs.—With the continued interruption to the stellar parallax programme, help is being given with the Cape programme of photographic astrometry. The zone $-56°$ to $-60°$ contains 96 plates, most of which have already been secured at the Cape, and 27 of which have reached Greenwich. Standard coordinates have been computed for all these plates, and 17 have been measured and reduced, giving results for 3,100 stars. The portion of the zone with right ascensions lying between 22^h and 4^h lies far from the Milky Way; additional plates with double the normal exposure of 8^m are being taken in this region in order to keep up the density of stars measurable at each section of the zone. A preliminary estimate of the precision to be expected, based on a comparison between the overlap of preceding and following plates, shows a probable error of about $\pm 0''{\cdot}10$ in both coordinates.

Yapp Reflector.—In 1946 January the main 36-inch mirror of the Yapp telescope was sent to Sir Howard Grubb, Parsons & Co. for aluminizing. The prisms and lenses of the 3-prism and the slitless spectrographs were also sent for "blooming" with an anti-reflection film. The telescope was overhauled and the mirror remounted in May, but owing to considerable delay in delivery of the other components the slit spectrograph was not ready for use till October. Since then 21 slit spectra of stars of types A to K, which had previously been photographed using a silvered mirror and uncoated prisms and lenses, have been secured for comparison purposes. The very marked improvement in photographic density shown in the ultra-violet region is doubtless due partly to the aluminizing and partly to the blooming, which was arranged so as to give the maximum efficiency in this region.

In order to obviate the considerable delays which occur when aluminizing and blooming are undertaken by commercial firms, a Metropolitan-Vickers plant for the vacuum deposition of optical coatings has been acquired through the courtesy of the Director of Scientific Research, Admiralty, and is in course of installation. It is capable of handling components up to 16 inches in diameter.

Photoheliograph and Spectrohelioscope.—The Sun was photographed on 269 days in 1946. There are no gaps in the combined Greenwich-Cape-Kodaikanal series for the year. Cape original and duplicate negatives have now been received up to 1945 December 30. Plates required to fill gaps in the combined series selected for measurement have been received from Kodaikanal up to 1942 December. Thirteen positives on glass have been kindly presented by the Superintendent, U.S. Naval Observatory, Washington, to represent days for which no photographs were obtained either at Greenwich, at the Cape, or at Kodaikanal during the years 1940-1944.

A series of solar negatives (scale: 3 inches=solar diameter) taken at a solar observatory on Kanzelhöhe, near Villach, in Upper Carinthia, Austria, have been received for the period 1945 April to 1946 May. This high altitude observatory (4,500 feet above sea-level), has offered to collaborate with Greenwich by sending the observational solar data being obtained there.

The measurement of 410 plates during the year has advanced the measurement of the combined daily series of Greenwich-Cape-Kodaikanal negatives from 1940 November 1 to 1943 December 8 (except for a few Kodaikanal plates now in transit to Greenwich). Heliographic positions and areas of sunspots have been computed up to 1941 August 15 for the combined series; computations for Greenwich plates alone have been advanced to 1945 June.

The Sun's disk was observed in $H\alpha$ with the spectrohelioscope on 173 days; on 25 of these, observation was possible only for 15 minutes or less. 214 measures for line-of-sight motions were made on normal patches of bright flocculi, most of these measures also giving effective line-widths of $H\alpha$. 337 measures were made on dark filaments on the disk and 33 measures on prominences at the limb. Line-of-sight velocities for dark filaments or prominences exceeded 100 km./sec. on five occasions. During the year, 156 sets of photometer measures were made collectively on normal bright flocculi and flares. With four flares the maximum central intensity exceeded that of the continuous photospheric spectrum 15 A. from the centre of $H\alpha$.

In all, 40 solar flares were recorded. The giant February sunspot provided a number of flares that permitted of observation at Greenwich, including three of major intensity. These flares were of immediate interest in connection with bursts of solar radiation observable on radio wave-lengths of about 5 m. as reported by Sir Edward Appleton.

The investigation into the occurrence of "sudden commencements" recorded on Greenwich magnetograms during 6 solar cycles, 1879-1944, has been completed. An account of the paper, presenting the results to the Royal Astronomical Society, is in *Observatory*, **66**, 371, 1946.

Time Department.—The Time Service has been operated throughout the year from the Abinger Magnetic Station. Some progress has been made in preparation for the installation of a reserve service from Greenwich, but owing to the delays in the carrying out of necessary alterations, and in the supply of the additional quartz clocks, it has only been possible so far to undertake a limited programme of work. Observations for the determination of time were resumed at Greenwich in August, and this resumption coincided with the commencement of a programme of observing and interchange of radio time signals for the determination of the longitude of Mount Stromlo Observatory in Australia.

During the months of August and September a regular interchange of small transit observers was maintained between Abinger and Greenwich. From August until Christmas a special rhythmic time signal transmitted from 18·55 to 19·00 U.T. from the Belconnen transmitter, and controlled from Mount Stromlo, was received at Abinger as regularly as conditions permitted. A rhombic aerial for the reception of these signals was erected on Wotton Common, near the Abinger Magnetic Station, and measurable signals were obtained on over 75 per cent of the transmissions. Mount Stromlo received the GKU3 18.00-hour short-wave transmission of the Abinger-controlled time signals, reception being improved after the General Post Office, in response to a request, transferred the GKU3 transmissions to an omni-directional aerial. Comparison of the results obtained during the final two months indicated that the adopted longitude of Mount Stromlo places the Observatory about 0·10 sec. too far to the east.

The total number of astronomical observations for the determination of time taken at Abinger during the year was 130, and at Greenwich during the period August to December, 58. Eight observations made at Edinburgh during January were also used. A new system of illumination of the field of the small transit is now in regular use at Abinger. Though certain improvements in the set-up remain to be effected, the appearance of the spider threads when illuminated by this method (see *Observatory*, **65**, 194, 1945) shows a distinct improvement upon that produced by the ordinary system of reflection of light from a flat placed in front of the O.G. at 45° to the axis of the telescope. The pivots of the Bamberg broken transit on loan from the Royal Observatory, Edinburgh, are in the process of being lapped after having been ground and plated with chromium. It is hoped that this instrument will shortly come into use, as the pivots of the instrument at present in use are showing marked indications of unevenness.

In addition to reception of the Australian signal mentioned above, reception of radio time signals from France, Russia and America has been maintained throughout the year. Transmission of the 10^h00 and 18^h00 rhythmic signals, controlled from Abinger, has continued on short-wave as well as on the original 16 kc./sec. The full installation of twelve crystal oscillators as planned at Abinger is now complete, but all the phonic motors are not yet delivered. Pending the delivery of the outstanding motors, the hourly and B.B.C. signals are still controlled from pendulum clocks. Rhythmic time signal transmissions are now normally based upon short-term predicted errors of three or four clocks, these being selected in accordance with the standard of their performance.

Daily comparisons have been made between those clocks incorporating synchronous

motors. Much trouble has continued to be experienced with the beat counters, for automatic comparisons, by which the clocks are compared at the high frequency stage. The research laboratories of the Post Office Radio Branch have been engaged upon this problem, and have now designed improved forms of beat indicators, which will be supplied for incorporation of the Observatory standards. The low power transmitter mentioned in the last report as having been set up at Abinger has continued to operate and has provided a useful link between the Abinger oscillators and those at other stations. The value of this transmission is now being very generally realized, and permission is being obtained to use a higher power. The necessary equipment is being prepared in the electronics laboratory, and it is hoped that the range of useful coverage will be greatly increased.

Construction of the Photographic Zenith Tube by Sir Howard Grubb, Parsons & Co. is proceeding. During the past year tests have been carried out in the laboratory at Abinger on a model of the plate carriage in order to test the rectilinearity of motion. The electronic frequency changer has also been tested and found satisfactory. Some experiments were made in connection with the photographic method of timing the carriage, and the design of the optical system for this has been settled, and suitable photographic plates selected. Consideration has now been given to the design of the mercury basin, and experimental equipment is in process of design. The special travelling microscope, made by the Cambridge Instrument Co. for measuring the photographic plates has now been tested and certain modifications effected.

Work on the Horizontal Transit Instrument has been interrupted by the more urgent demands of the photographic zenith tube. Progress has been made, however, in the development of an electrical system to actuate the drive of the variable-deviation system. A similar system is also being developed for use with an impersonal micrometer on the Bamberg transit instrument.

Nautical Almanac Office.—Although the general computational work for Admiralty Computing Service formally came to an end before the beginning of the year, several lengthy investigations carried over into 1946; they have now been completed. The Office has, however, taken over the computational work necessary for the latticing of charts required for the Decca system of navigation, and this has placed a heavy load on a staff already below normal strength. This work, although non-astronomical, has much in common with the astronomical computing work of the Office and is a natural extension of its navigational work.

Only little progress has been possible with the outstanding astronomical investigations; the 1943 occultations have been reduced and discussed, and will shortly be published together with a provisional determination of the corrections to the Moon's mean longitude and latitude for 1944 and 1945.

Difficulties of printing—particularly for the Air Almanac—have delayed publication of all the Office publications, but the calculations and preparation of copy are generally up to schedule.

For the first time since 1940, the whole of the computations for the volume of *Apparent Places of Fundamental Stars* for 1947 has been supplied by the Offices to which the calculations were originally allocated; in particular the Office of the *Connaissance des Temps* produced the ephemerides of both circumpolar and 10-day stars in time for the preparation of copy, although the 32 circumpolar stars were duplicated by the Office of the *American Ephemeris*, which had commenced the calculations before it was certain that they would be supplied from France.

Reprints of the volume of *Planetary Coordinates for the years* 1940–1960 (the stock of which was destroyed by fire), *Interpolation and Allied Tables*, and the *Five-figure Natural Trigonometrical Tables* (originally prepared for the War Office, but now being put on sale as an office publication) have been put in hand during the year, but no early publication can be expected.

Captain Fernandez de la Puente, Deputy Director of the Astronomical Observatory and Marine Institute, San Fernando, and two computers from the Office of the *Almanaque Nautico* spent three weeks in the Office learning mechanical methods of computation, in particular the application of the National Accounting Machine to the direct calculation of apparent places of stars.

Royal Observatory, Edinburgh

(Director, Professor W. M. H. Greaves, F.R.S., Astronomer Royal for Scotland)

Spectrophotometry.—The 36-inch reflector and spectrograph are being used for a spectrophotometric study of line intensities in early type spectra. During 1946 78 spectra were secured on 43 nights. Measurement of the spectra is keeping pace with the work at the telescope. The spectra are calibrated with a multiple slit spectrograph and are measured with a non-recording microphotometer of the Moll type, using a thermo-couple as the sensitive element. It is desirable to have comparison lines photographed with each spectrum, but it was feared that scattered light from the iron arc with which the Hilger spectrograph is fitted would be detrimental to the photometry. Accordingly, after some trials, the spectrograph has been fitted with an Osglim (Neon) lamp the light from which is transmitted through a blue filter. With this arrangement the comparison spectrum shows the prominent neon lines together with the helium and mercury lines.

Some studies have been made of the effect of simultaneous fog by a weak subsidiary source during exposure, a process which considerably increases the effective speed of the emulsion but introduces some difficulty in matching the fog in the stellar and calibration spectrographs.

The lamp of the calibration spectrograph has been fitted with an intermittent switch to imitate the exposure in the stellar spectrograph where the star image is repeatedly trailed along the slit.

Photometry.—The 10-inch triplet camera mounted in the West Dome has been cleaned and the individual lenses adjusted. A wire grating having 130 wires of 0·4 mm. diameter spaced at 2 mm. intervals was made in the Observatory workshop and fitted within the dew-cap, in preparation for a programme of stellar photometry.

It is planned to measure the plates with the 10-inch camera by means of a star actinometer. An instrument made by Messrs Kipp & Zonen of Delft for the Astronomical Laboratory at Groningen appeared the most suitable type, and after inspection a similar instrument with minor changes was ordered. It will deal with the 12-inch by 10-inch plates for which the 10-inch camera is designed and has special arrangements for recording objective prism spectra. The plate carrier of this instrument is provided with a movement allowing complete rotation.

Time Service.—This is now limited to the control of the time ball, time gun and various clocks in the City of Edinburgh. In order to avoid frequent interference with the pressures of the standard clocks a continuous motion "corrector" clock, made by Mr A. Steuart, has been acquired. This correcting device has a pendulum controlled

by one or other of the standard clocks, but is provided with a differential gear by which the phase of the emitted signal may be changed as desired.

Staff.—Mr John Storey retired on December 14 having completed nearly 52 years in the public service, of which 38½ years were spent at the Observatory. After having served as Computer and Established Computer at Greenwich he joined the Edinburgh staff as an Assistant on 1908 May 25. He was appointed Senior Assistant in 1909 and First Assistant in 1910. He relinquished the post of First Assistant in 1944 on the occasion of his formal retirement, but continued to serve in a temporary capacity at a time when his services were badly needed.

Dr E. A. Baker succeeded Mr Storey as First Assistant in 1944. Mr R. W. Wrigley retired in 1943.

Royal Observatory, Cape of Good Hope
(*Director, Dr J. Jackson, F.R.S., H.M. Astronomer*)

Reversible Transit Circle.—The observation of standard stars for the zones −56° to −64° was completed and the observation of similar stars for the zones −64° to −80° commenced on the same plan, i.e. allowing for reduction to the FK3 system by the observation of fundamental stars in the same zones. During the year 6155 transits were observed and 6120 zenith distances. The following observations were made of bodies in the solar system:—

Sun	162	Mars	12	Saturn	13
Moon	34	Vesta	11	Uranus	8
Mercury	74	Jupiter	11	Neptune	11
Venus	83				

The catalogue of 2400 standard stars for the zones −56° to −64° was completely reduced to the equinox of 1950.0 and the results are being typed so that a copy can be sent to Greenwich where the plates for the zones −56° to −60° are being measured. The probable errors of one observation derived from the internal discordances are only ±0″·194 in R.A. and ±0″·328 in declination.

Between the end of the one catalogue and the beginning of the other the instrument was completely overhauled. At this time the pivots were reground by the staff of the Mechanical Section of the Trigonometrical Survey of South Africa, to whom we owe a debt of gratitude. As a result of this regrinding, a completely new set of pivot errors had to be determined. The definitive set was obtained by the axis microscope method, as is used at the Naval Observatory, Washington, and which gives the figure of each pivot independently. Sets of observations were also made by the Airy method, as is used at Greenwich, and by a Krupp Gauge rigidly supported on the pier of the instrument. The results obtained by all three methods are closely accordant. The irregular bumps on the pivots have all been removed by the regrinding but the general ellipticity of the figure remains. The resulting pivot errors run smoothly and are smaller than they were but they are still rather large when they are compared with those of a modern instrument. But this is no real disadvantage provided that the corrections are well determined and can be applied without ambiguity. In this connection it is worth mentioning that the substantial accuracy of the pivot error corrections determined in 1938 and 1940 was confirmed by an examination of the east-west differences in right ascension for the 5373 stars observed between 1936 and 1944.

Photographic Zone Observations.—148 plates were taken. Of these 65 are for the zone $-56°$ to $-60°$ and 60 for the zone $-60°$ to $-64°$ with a normal exposure of 8 minutes. The remaining 23 plates were taken in the area from 22^h to 4^h of R.A. in the zone $-56°$ to $-60°$ with double the normal exposure as the star density is very low in this region of high galactic latitude. Only four plates have still to be taken to complete the photography of these zones. The Astronomer Royal has kindly undertaken to have the plates for zone $-56°$ to $-60°$ measured at Greenwich.

The work of measuring and reducing the plates of the lower zones has proceeded. The measurement of plates for the zone $-52°$ to $-56°$ was completed and reduced to give the difference between measured and computed positions. A considerable amount of work has been done on the 12,000 stars in the zone $-35°$ to $-40°$ where the final positions and proper motions are nearly complete. No proper motions for about one quarter of the stars can be derived for want of early observations of precision.

The heavy steel carriage for carrying the microscope of the long screw measuring machine has been replaced by a lighter one, and a new, lighter, and more efficient optical projection system has been constructed. The behaviour of the new system in actual practice has been very satisfactory and if repeated measures of the same star are made the internal agreement is better than formerly. The progressive errors of the screw have been re-investigated but show little change, the curve of the corrections required being of the original parabolic form.

Victoria Telescope.—During the year 3174 plates were taken for parallax determination and 103 for proper motion of the parallax stars. 1673 plates were measured and about 9000 await measurement. The parallaxes of 49 stars were determined, bringing the total since the programme started in 1926 to 1480.

The few additions to the working list consist of late type stars. Some of them are M type stars of moderate proper motion which have been replaced on the list. The taking of plates for proper motion has not been pushed forward as more accurate results will be obtained the longer we wait. It is proposed to undertake a new determination of the photographic and photovisual magnitudes of all stars for which the parallax has been measured.

Photographic and Photovisual Magnitudes.—During 1946 cooperation with the Radcliffe Observatory has been continued and steady progress has been made with the photometric programmes outlined in previous annual reports. During the year Dr Redman obtained 125 pairs of plates (photographic and photovisual) with the Cape cameras attached to the unfinished 74-inch reflector. Of these, 24 pairs were of the Southern Eros Comparison Stars, 8 pairs of the Praesepe Cluster, 23 pairs for intercomparing the E regions with one another and the remaining 70 pairs were for the zones between $-52°$ and $-64°$. Observations for these zones are now complete between 18 and 6 hours of R.A. Seventy more pairs of plates are required to complete the present programme and it is hoped that all of these may be obtained during the first half of 1947.

Once again a considerable amount of time has been devoted to the attempt to set up accurate magnitude sequences in the nine E regions which have been used as the basis of our photometric work. During the year a start has been made on extending the range of the sequences by measuring all the stars brighter than $8^m{\cdot}0$ pg. in areas of $6° \times 6°$ surrounding each E region and by measuring selected faint stars down to $14^m{\cdot}0$ pg. on plates taken with the Victoria Telescope. Dr Redman has provided a reliable framework for the reduction of these measures by means of observations—both photo-

graphic and photovisual—made at Pretoria with a Fabry photometer. There is now so much high quality observational material in hand, that by far the greater part of the work needing immediate attention consists of the measur ment and reduction of plates already taken, and of a critical discussion of the measures already made.

Mr H. C. Davies has made steady progress with the observation for the photographic (blue) magnitudes by means of a Fabry photometer attached to the Astrographic Telescope, of stars south of the equator for which the H.R. magnitudes are brighter than 5·0. The programme has been enlarged to include stars to 6° north declination, which culminate within 40° of the zenith, so as to provide a stronger overlap with similar work in the northern hemisphere. Since he began in 1945 Mr Davies has obtained 60 plates which have given 1286 magnitude determinations for 643 stars. The reduction of the measures is up to date. All the earlier plates, which were originally reduced by means of Dr Knox-Shaw's visual magnitudes corrected by an assumed colour index, have been re-reduced during the year and a system of photographic magnitudes built up which is completely independent of all previous observations.

The modified Schilt photometer was in constant use throughout the year and gave no trouble whatsoever. During 1946 just over 76,500 images were measured with it. Of these

36,400 were on plates of the −35° to −40° zone.
12,800 on parallax plates taken with the Victoria Telescope.
12,500 on plates of the E regions—stars brighter than $8^{m}\cdot0$.
3,600 on plates of the E regions taken with the Victoria Telescope.
1,950 on plates of the Southern Eros Comparison Stars.
4,560 on plates taken with Fabry photometer by Mr Davies.
3,600 on films taken by Mr Cousins with his Fabry photometer attached to the Natal Observatory Telescope.
1,100 on experimental plates testing methods of development, on plates of a variable star, etc.

After the end of the routine measurements of the −35° to −40° zone, the method of reading the galvanometer was altered. The original Schilt method of reading the reflection of the scale in the mirror of the galvanometer through the same eye-piece that is used for locating the image on the plate was replaced by the more usual method of using the galvanometer mirror to reflect the image of a fixed brightly illuminated slit on to a semi-transparent scale. The new scale, which is more open than the old, consists of two parts, a primary scale divided into 100 and a sliding device which enables the reading to be read off immediately as a percentage, even though the clear film reading does not correspond exactly to the 100 division mark on the primary scale. The new scale has worked very well and has resulted in the saving of a large amount of office time that had formerly to be devoted to reducing the galvanometer readings to percentages. The idea of the sliding device originated in talks with Dr Wesselink of the Leiden Southern Station when he visited the Observatory in May.

Photoheliograph. The sun was photographed on 337 days, 694 plates being taken in all. Of these plates 24 had double exposures for the determination of the zero of position angle. Visual observations of this quantity have been made weekly.

Occultations.—Seventy-one observations of 40 phenomena were observed by various observers with telescopes at the Observatory. No less than 18 of the observations were re-appearances. The results of these observations together with 10 observations

made by Mr Krumm in Cape Town and 7 made by Mr Cousins in Durban are being forwarded to the Nautical Almanac Office for final reduction.

Variable Stars.—During the past year Mr de Kock has used the 6-inch refractor to make 4328 separate estimates of brightness of a selected list of 121 long-period variable stars. As far as possible, he tries to observe each star every fifth night or morning. The observations have, as usual, been forwarded to Harvard, the headquarters of the American Association of Variable Star Observers.

Publications.—As a result of the war the publication of results was stopped and it may be of interest to astronomers to know what results are ready or nearly ready for publication.

(1) Second Cape Catalogue for 1925.0 based on observations made in the years 1925 32 This contains 8400 stars down to magnitude 7·5 or somewhat fainter, south of −30°, and 3267 Zodiacal Stars.

(2) Third Cape Catalogue for 1925 0 based on observations made in the years 1932–36. The working list contained 7415 stars down to magnitude 7·5 between the equator and −30° declination.

(3) First Cape Catalogue for 1950.0 based on observations made in the years 1936–44. This catalogue contains 5373 of the most important stars south of declination +30°, many of which had been omitted from (1) and (2).

(4) Observations have been made by photography for the zones −30° to −35°, −35° to −40°, −52° to −56°, −56° to −60°, and −60° to −64°. The first three zones have been measured at the Cape, the MS. for the first is nearly complete, calculations for the second nearly complete. The final catalogues will give positions, proper motions, magnitudes (photographic and photovisual) and spectral types for about 10 stars per square degree. The positions will depend on meridian observations made about the time the plates were taken.

(5) Observations of the Sun, Mercury and Venus made in the years 1925–1936 are ready for printing.

(6) Details of the determination of the parallax of stars in the Fifth to the Fifteenth Lists for which the final results were published in the *Monthly Notices* between 1933 and 1945 (983 stars).

Cambridge Observatories
(*Director, Professor F. J. M. Stratton*)

The University Observatory and the Solar Physics Observatory have this year been combined under one Director, with two Assistant Directors, one Observer in Meteorological Physics and five assistant observers.

Photoelectric work on Uranus has been continued with a view to detecting variations in the Solar Constant. The photoelectric photometer on the Sheepshanks telescope has been modified to make possible its easy removal from or replacement on the telescope. This makes possible the use of the telescope for direct photography on nights not good enough for photometry. A caesium oxide cell has been taken into use. The photographic programme is the re-observation for proper motions of areas photographed by Hinks forty years ago.

The Wood grating has been mounted on the Newall telescope for a study of the *Ca*II triplet in the infra-red in stellar spectra of different types.

The Huggins refractor has been brought back into use again for a study of spectra

of certain binary stars and the 3-foot reflector for photographic photometry of extra-galactic nebulae through various filters. The mirror has now been aluminized.

A radio programme on long delay echoes has been started in the hope of securing evidence of extra-terrestrial streams or currents of particles; close touch is being maintained with the Field Radio Station of the Cavendish Laboratory which is studying solar radiations of radio frequency. The spectrohelioscope has been brought back into regular use but various delays have prevented the restarting of routine observations with the spectroheliograph. Negatives of spectroheliograms in K_{232} light are once more being received from Kodaikanal Observatory.

The McClean spectrograph is being used for a study of solar spectra for special disturbed regions on the Sun's disk in connection with sunspots and flares, while the Rowland 21-foot concave grating has been used for securing spectrograms of the H and K lines of the solar spectrum on the occasion of the presence of large active sunspot groups.

The components of the rock-salt prism spectrograph desired for a study of the solar infra-red spectrum have at last been received and work on extinction coefficients of atmospheric gases under a wide range of physical conditions has been commenced.

Thunderstorm observations have been resumed with the cooperation of the Meteorological Office Thunderstorm Locating Unit. For storms at a distance of over 20 km. a study is being made of the statistics of the signs of field-changes due to lightning discharges and of the electric moments of the discharge. The relative magnitude of the radiation and electrostatic components of field-changes due to discharges at various distances is also being examined. Attempts are being made to correlate short period fluctuations in the fine-weather electric field with turbulence and other meteorological factors.

University Observatory, Glasgow
(*Director, Professor W. M. Smart*)

The study of the systematic motions of the stars, based on the data of the *General Catalogue*, has continued.

The Director has been engaged in some problems in navigation.

University Observatory, Oxford
(*Director, Professor H. H. Plaskett*)

Staff.—Following his move to Kew Observatory with the International Seismological Summary, Mr J. S. Hughes resigned his appointment as Chief Assistant on 1946 December 31. Dr G. Merton has been working at the Observatory in a voluntary capacity since the beginning of May, and the Rev. P. J. Treanor, elected by Balliol College to a Skynner Senior Studentship in Astronomy, commenced work in October.

Buildings.—Erection was commenced in November of a new dome over the solar telescope. The old dome, erected in 1875, was not only a serious handicap to observation because of its narrow sliding-panel shutter, but by the end of the war was almost beyond repair.

Solar Work.—Messrs Adam Hilger Ltd. completed refiguring the two 60 -prisms in the first half of the year, and at the same time " bloomed " all the optical parts of the spectroscope. The instrument was re-assembled in July, and showed a marked improvement in definition and a great increase in speed. In spite of an exceedingly

bad observing season, Dr Adam was able to get a complete set of spectra for limb-effect, using the equivalent 5-prism dispersion of the spectroscope crossed with a Fabry-Perot etalon. These new spectra are so superior to the single-prism spectra obtained in 1945 that it is probable that her final results will be based almost entirely on the 1946 material. P. J. Treanor has commenced a study of line-profile determination. It is planned to compare the results from three different methods of determination, all involving the use of a Fabry-Perot etalon with the solar spectroscope, and to establish the limits of accuracy attainable in this difficult problem. Preliminary work on the reflectivity of etalon coatings is well advanced.

Imperial College Observatory, South Kensington, London
(Director, Assistant-Professor R. W. B. Pearse)

During the year the Observatory has been brought into use again for teaching. The roof has been repaired and the 6-inch refracting telescope has been thoroughly overhauled. The courses of instruction in astronomy and spectroscopy have been well attended.

Work on the production and analysis of molecular spectra of astrophysical interest has been resumed. The construction of a lithium fluoride spectrograph which was set aside during the war is being continued with the aid of a grant from the Government Grant Committee of the Royal Society.

The department suffered two losses this year. Professor H. Dingle resigned to occupy the chair of the History and Philosophy of Science at University College. Mr J. H. Strong, a member of the expedition to Araxa sponsored by the Joint Permanent Eclipse Committee, lost his life as a result of the tragic aeroplane accident at Dakar.

University of London Observatory, Mill Hill, and
University College Observatory
(Director, Mr C. C. L. Gregory, Wilson Observer)

Radcliffe Telescope.—This instrument was used on 143 nights, during which observations made before and after midnight were 94 and 74 respectively. The total number of plates taken was 566, of which 530 were for parallax, 16 for proper motion, 2 on comets and 1 on asteroid Nemausa 51, two positions of which were published in I.A.U. Circular No. 1060. The remainder were test plates, taken when the instrument was being adjusted prior to the recommencement of the parallax programme, on April 2, after an interval of six and a half years.

During the last two months of the year some difficulty was experienced, in the early evening, on account of a drop in the frequency of the electric mains supply, which caused the synchronous driving motor to run too slowly to be within the range of the pendulum control mechanism.

The electric hoist for the rising floor of this observatory, mentioned in the last annual report, has worked satisfactorily throughout the year.

Other instruments.—The Wilson 24-inch reflector and 4-prism spectrograph were used mainly on γ Cassiopeiae. No conspicuous changes in its spectrum were observed.

A spectrogram of T Coronae Borealis, obtained during the recent outburst, was measured and the results communicated to the Society.

A portable transit instrument, a 6-inch Cooke equatorial refractor, together with some minor astronomical instruments, were moved to the University Observatory from University College to provide for student instruction. The $3\frac{1}{2}$-inch transit circle was also moved from the College but has not been re-erected.

On the occasion of the annual visitation of the Board of Visitors on April 27 it was proposed by the Astronomer Royal that the possibility of designing and making a mirror meridian instrument should be investigated. A provisional model has been constructed in the Observatory workshop. This was displayed in the Society's library before the meeting on November 8, and plans for the completed instrument are being worked out by the Optical Works Ltd. in collaboration with the Director.

University Observatory, St. Andrews
(*Director, Dr E. Finlay-Freundlich*)

The Department of Astronomy and the Observatory, both created in the first years of the war, are being completed now that the war has ended.

It was decided to equip the Observatory with a 30–36-inch Schmidt-Cassegrain telescope, which will be constructed in our workshop as part of a research project. Mr Robert Waland of Dumfries has joined the department as Research Assistant to the Observatory, together with his assistant Mr W. Threadgill, and has been entrusted with the construction of the telescope. Dr E. H. Linfoot, of Bristol University, has accepted our invitation to take charge of the theoretical optical side of the project as temporary external collaborator of the department. Installation of the workshop equipment is completed, and good progress has been made with the construction of the grinding and polishing machine, designed by Mr Waland.

It is planned to make a half-size pilot-model before undertaking the construction of the 36-inch correcting plate.

Theoretical work on the structure of the globular star-clusters has been continued. Mr Ian Campbell, M.A., has joined the department as Assistant Lecturer and is taking part in this theoretical work.

Norman Lockyer Observatory, Sidmouth
(*Director, Mr D. L. Edwards*)

The weather in 1946 was one of the poorest, from the point of view of night work, in the history of the Observatory. In particular, the first-class nights required for photometric work (which forms the basis of most of the observing programmes) have been very infrequent. All the best nights have been utilized for such work, while other nights have been mainly devoted to miscellaneous work, especially to testing various photographic emulsions with a view to standardizing on three or four of the most suitable for the various programmes.

Colour temperature observations have now been fully re-organized; a number of plates of primary and secondary standard stars have been obtained, and some trial exposures secured in the near infra-red. A special investigation of the gradients of γ Cassiopeiae is included in this work.

Work on the spectra of γ Cassiopeiae and on spectrum changes in ι Herculis has also been continued. The galactic cluster survey is at present still in abeyance, owing to shortage of staff.

Dominion Observatory, Ottawa, Canada
(*Director, Dr C. S. Beals*)

Staff.—Several major changes in the staff have occurred during the year. Mr R. Meldrum Stewart retired as Dominion Astronomer on August 15, a position which he had held since held 1924. Dr Ralph E. DeLury succeeded him, directing the

work of the institution until November 23, when he also retired. The vacancy was filled by the transfer of Dr C. S. Beals from the Dominion Astrophysical Observatory at Victoria, who began his duties on November 24. Squadron Leader P. M. Millman of the Royal Canadian Air Force joined the staff of the Observatory as astronomer on June 15.

Meridian Work and Time Service.—Work with the Meridian Circle was continued on a list of Backlund-Hough stars under the direction of Mr W. S. McClenahan. The instrument was not used during part of April, May and June, when it was thoroughly cleaned and painted. At that time also a change was made in the method of adjusting the right ascension wires. This was done in the Observatory machine shop. Observations were taken on 48 nights, resulting in 978 transits and zenith distances. 157 readings of Nadir and 88 observations for instrumental constants were taken. Considerable progress was made towards completing the computations of observations taken 1912 to 1923. Mr G. E. Woolsey joined the staff during the year.

With a reversible transit, observations for clock corrections were taken on 218 nights. The primary clocks were compared twice daily. Daily time signals were transmitted throughout the year, controlled by the time signals machine. Plans have been made to obtain better and more powerful transmitters for the continuous short-wave transmission. The signals now go each day for a period of two minutes to the Canadian National and the Canadian Pacific Railways. Signals were broadcast over station VAA, Department of Transport, from dusk to dawn from May to October, for the use of surveyors in Northern and Western Canada. The clock systems, in the various government buildings, synchronized from the Observatory, continued to run satisfactorily. Many clocks, watches and chronometers were repaired and rated. Tables of times of sunrise, sunset, moonrise and moonset, and information in regard to eclipses, were furnished when required. Consideration was given to a project of erecting a photographic zenith tube to be used in connection with the time service.

Solar Physics.—Photographs of the Sun were taken on 53 days. Eleven plates were taken of the partial eclipse of November 23. Photographic prints were supplied to the Canadian Radio Wave Propagation Committee and the National Research Council. A statistical analysis was made of 589 solar rotation observations taken in 1914.

Meteor Research.—Dr P. M. Millman continued with research in the field of meteoric astronomy, previously carried out at the David Dunlap Observatory and interrupted by the war. Photographic observations, both direct and spectroscopic, were made of the Perseid meteors on August 11–13 and of the Giacobinid meteors on October 9. Three Perseid spectra secured on the first programme confirm the results previously published for these meteors. Some twenty Giacobinid spectra, secured on the second programme, all show the lines of neutral sodium, iron, magnesium, manganese and possibly calcium. Lines of ionized elements, present in Perseid spectra, do not appear in Giacobinid spectra. A preliminary analysis of meteor rates indicates the Giacobinid maximum at $03^h\ 52^m$ U.T., 1946 October 10.

Seismology.—During the calendar year of 1946, 594 earthquakes were recorded at stations of the Canadian network.

Teleseismic seismographs have been maintained in continuous operation at Victoria, Saskatoon, Ottawa, Seven Falls and Halifax, and in addition short-period instruments have been operated at Ottawa, Shawinigan Falls and Seven Falls, the last two named stations in cooperation with the Shawinigan Water and Power Co. and the Quebec Power Co. respectively.

All Canadian registrations have been regularly reported through the medium of a monthly bulletin service. Reports on the records obtained at the two Quebec stations have been prepared each month and distributed to the officials of the cooperating agencies.

On 1946 June 23, a major earthquake occurred on Vancouver Island, B.C., probably the most severe shock which has occurred in Canada within historic times. Dr E. A. Hodgson, Chief of the Seismological Division, in the course of a field study of the earthquake, found that displacements in terrain, practically all downward, had taken place along the central east coast of the Island. On the land the maximum drop was of the order of forty feet. In the water differences as great as a hundred feet were noted. Some submarine depth changes were found also in the Alberni Inlet. A report of the field study was published in the October–November issue of the *Journal of the Royal Astronomical Society of Canada.*

Terrestrial Magnetism.—During the year magnetic observations under the direction of Mr R. G. Madill were made at sixty-five stations, comprising one in Labrador, seventeen in Quebec, seven in Ontario, one in Manitoba, three in Saskatchewan, one in Alberta, eight in British Columbia and twenty-seven in the North-West Territories. Field instruments were compared with standards at Ottawa and Agincourt. The magnetic observatories at Agincourt, Ontario, and Meanook, Alberta, continued to operate in a normal manner. A temporary magnetic observatory operated at Baker Lake, N.W.T., for about three months in connection with Exercise Musk-Ox. Base stations for vertical force were established in mining areas in Ontario and Quebec for the use of geophysical prospectors.

Observations for declination, inclination and total force, made in Arctic areas contiguous to Boothia Peninsula, indicate strongly that the north magnetic pole is presently located in Somerset Island and about two hundred miles northerly from the position established by Amundsen in 1904.

Gravity.—Seventeen gravity stations were established with the pendulum apparatus, and except for some more northerly stations were intended to provide control for operations with the gravimeter.

A gravimeter was purchased from the Atlas Exploration Company of Houston, Texas, in July, and under the direction of Mr A. H. Miller three hundred observations were taken with it and a vertical magnetometer along two traverses across the southern portion of the prairie provinces.

One hundred and fifty stations were established with the gravimeter along the highway between Winnipeg and Ottawa and one hundred and sixty in southern Ontario and Quebec to complete networks begun the previous season with the gravimeter then on loan from the Humble Oil and Refining Company.

Since 1944 seventeen hundred gravimeter stations have been established in Canada by the Observatory. Bouguer anomalies have been computed for 820 in Eastern Canada. The anomalies are definitely related to the occurrence of certain geological formations.

David Dunlap Observatory, University of Toronto
(*Director, Professor F. S. Hogg*)

This review covers the last five years of the work of the David Dunlap Observatory. In 1946 Professor R. K. Young retired, and was appointed Director Emeritus. Dr Millman resigned from the staff in 1945, to enter the permanent Air Force, and later

to join the staff of the Dominion Observatory. Professor Heard returned after over five years in the R.C.A.F., and Dr Ralph E. Williamson of Cornell has joined the staff. Professor Yü, Director of the Nanking Observatory, is serving as visiting lecturer and astronomer.

Completed Programmes.—While absence of members of the staff caused suspension of most of the individual researches, it was found possible to operate the 74-inch telescope almost full time on the routine observational programmes. Two radial velocity catalogues were published. The first of these *D.D.O. Pub.*, **1**, No. 13, gives the velocities of 374 stars, down to photographic magnitude 7·5, in areas 6×6 degrees, centred about Kapteyn Areas. *D.D.O. Pub.*, **1**, No. 16 gives the velocities of 681 stars. These were selected as being all the northern stars Ao and later, previously not observed for velocity, from Schlesinger's *Catalogue of Bright Stars*. The orbits of six spectroscopic binaries were also published.

Dr Helen Sawyer Hogg has continued her work on variable stars in globular clusters. The light curves of the variables in M 4, M 13, M 22, M 80 and NGC 5466 have been published, as well as the discovery of new variables in NGC 6273, 6284, 6287 and 6293, four globular clusters in Ophiucus.

New Programmes.—The curent radial-velocity programmes include later type stars brighter than 9·0 photographically, in the Yale Zone +25° to +30°. These stars are well distributed in galactic latitude for studies of motions perpendicular to the galaxy. Spectrograms of a large number of stars of well determined absolute magnitude have been secured for calibration of absolute magnitude criteria for use with our collection of radial-velocity plates. Professor Heard has resumed his studies of wave lengths and intensities in the spectra of Be stars, and of velocity changes in β Canis Majoris type stars. Professor Yü is commencing spectrophotometric studies, particularly of A type stars.

Instruments.—A great gain in speed of the spectrograph was secured in 1942, when the lenses and prisms were treated with low reflection coatings. A projection measuring machine was constructed for the measurement of spectrograms. New projects include resumption of construction of a spectrograph using a fine Wood aluminum on glass grating secured just before the war, and of a photoelectric photometer for use with the 19-inch and 74-inch reflectors.

D.D.O. Pubs., **1**, Nos. 11–19 and *Comm.*, Nos. 8–12 have been published during the interval.

Union Observatory, Johannesburg
(*Union Astronomer, Dr W. H. van den Bos*)

During the year 515 micrometrical measures of double stars were obtained with the 26½-inch refractor. With the 9-inch visual refractor 86 occultations have been observed.

Plates obtained with the Franklin-Adams Star Camera amounted to 313 :

Minor Planets	218
Comets	73
Variable Stars	8
Miscellaneous	14

A daily record of sunspots has been kept since August 26. Visitors have again been admitted since October; 310 persons attended on visiting evenings.

Mr E. L. Johnson returned to the Observatory in April from active service. Mr J. Hers joined the staff on November 1. Dr H. van Gent returned to Leiden Observatory, his place being taken by Dr A. J. Wesselink.

Radcliffe Observatory, Pretoria
(*Director, Dr H. Knox-Shaw, Radcliffe Observer*)

It has been a disappointing year, the 74-inch mirror and the Cassegrain spectrograph being little, if any, nearer completion at the end of it than they were at its beginning. Dr D. S. Evans, who was appointed to the staff in 1945 November, reached Pretoria at the end of August 1946. He has been engaged on constructing a prismatic camera from a $4\frac{1}{2}$-inch Cooke lens, kindly lent by the Cape Observatory, and a 60° prism from the Cambridge eclipse spectrograph, with which he intends to measure colour temperatures of the brighter stars of early type. Before coming to South Africa he wrote a paper on the electromagnetic forces in solar prominences.

Dr Redman has continued the stellar magnitude work undertaken in collaboration with the Cape Observatory. After completing the photography of the zone −35° to −40°, he commenced that of −52° to −64°, and the half of this zone between R.A. 6^h and 18^h, involving 65 pairs of plates, has been finished. In addition further progress has been made in establishing standard magnitudes in the Harvard E regions at −45°, and intercomparisons have been made between these regions and with the Eros fields and Praesepe. Some time has been spent on designing a coudé spectrograph for the 74-inch reflector.

The Director has nearly completed a revised system of homogeneous magnitudes of stars south of the equator based on the Harvard photometric magnitudes. The number of stars involved is about 20,000.

Nizamiah Observatory, Hyderabad
(*Director, Dr Akbar Ali*)

Little work was done with the Astrographic telescope on account of the great delay experienced in obtaining photographic plates from England. Almost all the remaining good plates of Eros (1931 opposition) have been measured, and their reductions are in progress. Revision of the plate constants in zone −17° is nearing completion. A list of proper motions of faint stars in the Hyderabad Astrographic catalogues, zones −17° to −19° is almost ready for publication.

The total number of occultations observed during the year was 14; they have been reduced and their results are, as usual, being communicated for publication in the *Monthly Notices*. The paucity of the observed occultations is due to the unusually bad weather prevalent during the period under report. The programme of measurement of double stars has been continued as before.

The routine observations of the Sun with the spectrohelioscope have been continued as before.

The following copies of the *Astrographic Catalogue* have been distributed :—

1. Vol. XIII, Part I, giving the revised values of the plate constants in zones +36° to +39°.
2. Vol. XII, zone +36°.

The meteorological and seismological work of the department has been continued as usual.

Mr Syed Ahmed, Assistant, and Mr Ananthanarayan, Computer, retired during the year.

Solar Physics Observatory, Kodaikanal
(*Director, Dr A. K. Das*)

General.—Dr A. L. Narayan went on leave preparatory to retirement in 1946 July and Dr A. K. Das assumed charge as Director. Dr R. Ananthakrishnan joined as Assistant Director in September.

Fifty K and $H\alpha$ flocculus plates for the year 1940 from Meudon Observatory, and 747 $H\alpha$ flocculus and K Prominence plates relating to the years 1940–44 from Mount Wilson, were received during the year. For the period 1940–42, 434 K and $H\alpha$ flocculus plates were supplied to Meudon Observatory, 141 K flocculus plates for the period 1943 October to 1944 March to Solar Physics Observatory, Cambridge, and 39 photoheliograms for the years 1941–42 to the Astronomer Royal, Greenwich Observatory.

Routine Observations.—Weather conditions were generally less favourable than during the previous year, especially during the last two months of the year, on account of the unusual activity of the North-east monsoon. The definition of the solar image before 11^h I.S.T. estimated on a scale in which 1 is the worst and 5 is the best, was 2 or less on 94 days and 4 or more on 52 days; the mean value of definition was 2·7.

The routine observations with the photoheliograph, the spectroheliograph, the prominence spectroscope and the spectrohelioscope were continued as in the previous year. The $H\alpha$ spectroheliograph was completely rebuilt in June–July and as a result it became possible to obtain photographs on 275 days as against 270 of the previous year in spite of less favourable weather conditions. Calcium flocculus plates were obtained on 270 days and calcium prominence plates on 258 days. Direct photographs of the Sun on a scale of 8 inches to the Sun's diameter were obtained on 292 days. Quarterly statements of chromospheric eruptions observed with the spectrohelioscope together with the times of observations were sent to Professor Brunner of Zürich.

Sunspots.—The number of new sunspot groups observed during the different months of the year, their distribution in the two hemispheres, and the mean daily numbers are given in the table below :—

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year
No. of groups	16	24	23	20	26	21	26	16	25	40	33	22	292
North	9	12	7	3	14	9	14	11	14	20	14	9	136
South	7	12	16	17	12	12	12	5	11	20	19	13	156
Mean daily number	3·6	6·1	5·6	5·6	5·7	4·6	5·5	4·4	5·9	7·1	7·5	6·5	5·7

There were no days on which the Sun's disk was free from spots as against 35 spot-free days of the previous year. Compared with 1945, there was an increase of 165 per cent in the new spot groups and 185 per cent in the mean daily number of sunspots. The approximate mean latitude of the spots for the whole year was 20°, as against 25° of the previous year. About 20 per cent of the total number of new spots appeared in latitudes higher than 25°. Bright reversals of the $H\alpha$ line were observed on 92 occasions and dark reversals of the D_3 line on 48 occasions. Displacements of the $H\alpha$ line towards the violet were observed on 13 occasions and towards the red on 22 occasions near spot groups.

Research Work.—In connection with a programme of investigational work on the magnetism of sunspots, the construction of a coelostat and of a new spectrograph of high dispersion and resolving power was taken up and mostly completed.

Commonwealth Observatory, Mount Stromlo, Canberra
(Commonwealth Astronomer, Dr R. v. d. R. Woolley)

Time Service.—A total of 220 time observations with the small reversible transit was obtained. Since 1946 August 1, rhythmic time signals have been broadcast via Belconnen Naval Wireless Station. A re-determination of the longitude of the Observatory is being carried out with the collaboration of the Astronomer Royal. Radio time signals have been exchanged with Greenwich since 1946 August 1. A considerable amount of auxiliary equipment has been brought into operation, including a personal equation machine and several electronic devices to ensure accuracy and convenience in the signalling circuits.

Double Stars.—The programme of double star observation was continued with the 9-inch Oddie refractor, and a comparison image micrometer was constructed and mounted on this telescope. Double star observations were obtained as follows :—

Separation	Over 2″	2″–1″	Under 1″	Total
Filar Micrometer	227	313	219	759
Comparison Image Micrometer	9	13	5	27

Variable Stars.—Using a sodium cell on the Reynolds 30-inch reflector, photoelectric light curves were obtained for V Puppis (114 observations on 21 nights) and μ^1 Scorpii (412 observations on 42 nights). The results for the former star have been communicated to the Society.

Solar Observations.—In collaboration with the Council for Scientific and Industrial Research, records have been obtained of a 200 Mc. electromagnetic radiation from the Sun. A correlation has been sought between the intensity of this radiation and such solar phenomena as flares, high velocity dark markings, magnetic polarity of spots, flare and bomb spectra and absorption in the λ 5875 line of *He*. Circular polarization of the radiation relative to meridian passage of spots has been investigated. Equipment, including a photocell mounting, neutral filters and a spectrograph, has been constructed for a re-determination of the Sun's stellar magnitude.

Ionosphere.—Predictions of ionospheric disturbances likely to affect radio communications have been issued during the year. The predictions are based on solar, ionospheric and geomagnetic data. A new ionospheric recorder has been brought into operation.

Instruments.—Modifications to the 30-inch Reynolds reflector have included tube bracing, installation of electrical slow motions and synchronous motor drive and new Cassegrain mirror mounting. Optical parts have been made for a slitless spectrograph for use with the Reynolds telescope. Minor alterations have been made to the solar tower telescope including the addition of a divided circle and small telescope to facilitate setting on stars. The 9-inch Oddie and the 6-inch Farnham refractors have been reconditioned. Negotiations are in train for the purchase of a zenith tube telescope and a quartz clock installation. Work has been carried out on a stellar photometer embodying an electron multiplier tube.

Workshop.—The Observatory has received a valuable selection of workshop equipment as a result of transfers from the Commonwealth Machine Tools Pool.

Staff.—Additions to the staff during the year include Mr D. G. Thomas and Dr G. V. Simonow. Messrs Dawson and Odgers resigned, the latter to pursue studies at the Solar Physics Observatory, Cambridge.

Riverview College Observatory, Riverview, N.S.W.
(Director, Rev. D. O'Connell, S.J.)

The Rev. T. N. Burke-Gaffney, S.J., joined the staff at the beginning of 1946.

Dr J. G. Voûte, former Director of the Bosscha Observatory, Lembang, Java, has been staying at Riverview since early in 1946, recuperating from the effects of the war years in Java. He is preparing for publication his work on double stars (11,000 measures made during the war) and his work on variable stars.

Measures of solar radiation and sky radiation made at Riverview with pyrheliometers and pyranometer have been reduced and are being published in *Riverview Publication* No. 6. *Publication* No. 7 (mainly studies of variable stars) is also with the printer.

Sydney Observatory
(Government Astronomer, H. W. Wood)

The programme of work on the *Astrographic Catalogue* has been continued and during the year Vols. 18 and 20 have been issued. With the object of determining proper motions of some galactic clusters in the zone, photographs through the glass have been taken for some centres for which plates of old epoch are available.

The occultations predicted in the *Nautical Almanac* have been observed when possible and are now being reduced. The programme of observations of double stars has been continued and an orbit computed for h 3494. Measurements are being made of double stars appearing on plates taken for the *Astrographic Catologue*. A note " Nomograms for Some Astronomical Calculations " was published by the Director in the *Journal and Proceedings of the Royal Society of New South Wales*, reprinted and issued as *Sydney Observatory Papers*, No. 1.

The civil work consisting of the supply of astronomical information for legal purposes, the time service and answering general inquiries has been carried on. The educational work of the Observatory was continued and lectures and demonstrations on astronomy were delivered regularly.

Carter Observatory, Wellington, New Zealand
(Director, Mr I. L. Thomsen)

Educational.—The Observatory has been used extensively by the public on Friday evenings, as well as by schools and clubs by special arrangement on other evenings. A course of sixteen lectures on practical astronomy was given to a formed class of amateurs. Up to the time of writing, attendances from visitors amount to 2400 for the year.

Solar Work.—Regular observations of sunspots have been carried out with a 5-inch telescope by projection, and similar observations have been received from the New Plymouth Astronomical Society. Sunspot numbers, determined from these observations, have been forwarded to the Swiss Federal Observatory at Zürich.

More systematic observations have been begun with the spectrohelioscope.

Aurora Australis.—Reports on displays of the aurora australis have been received from about 300 voluntary observers in New Zealand, from observers in Australia and Tasmania, and from the scientific party stationed on Campbell Island. These reports are still in process of reduction, and a study is being made of relationships with solar and magnetic activity.

Jupiter.—A series of disk drawings, as well as transits across the C.M. of prominent features, was made during the 1946 opposition with the 9-inch refractor. The results still await reduction.

Occultations.—Observations of occultations made at Wellington, New Plymouth and Dunedin from 1941 to 1945 inclusive, were collected and forwarded to H.M. Nautical Almanac Office. Observations for 1946 are being collected in a similar manner.

Comets.—Approximate reductions of positions from field drawings were made from observations by Mr A. Jones of Timaru, who discovered a comet on 1946 August 8. Notice of discovery, as well as positions, were forwarded to the I.A.U. through Canberra, as well as Harvard College Observatory.

An investigation was made of negatives obtained by Mr D. C. Berry, Dunedin, showing a comet-like object on September 2, 3 and 4. The positions were reported to the I.A.U., but the possibility of its reality is still in doubt.

Daylight Meteor.—Some hundreds of observations of a daylight meteor seen on 1946 July 8 were received and a rough preliminary path obtained. The reports have been handed to the Meteor Section of the Astronomical Society of New Zealand for a precise determination.

General.—The 9-inch equatorial was adjusted for altitude, but still requires adjustment in azimuth. The present lack of an illumination system has prevented micrometer or stellar photographic work being undertaken.

The geographical coordinates of the 9-inch equatorial were determined and forwarded to H.M. Nautical Almanac Office.

Future Work.—Plans are in hand for the design and construction of a new solar camera with a view to precise study of movements of umbral nuclei, in cooperation with Zürich.

Staff.—The Observatory is sadly lacking in staff, there being only one lady assistant, Miss K. Turner. Mr R. Humphrey was employed part-time for a few months.

Mr Robert Barker's Observatory, Cheshunt, Hertfordshire

Mars's opposition was not productive of results above the average at Cheshunt. About 40 canals were recognized and these linear markings were often more definite than the outlines of the maria.

Trivium Charontis varied in shape and presentation, and was sometimes difficult, although the canals radiating from this great junction were generally clearly defined.

Despite the poor seeing of the year, some new lunar features were discovered, including a long straight cleft joining Manners to the great Ariadaeus Cleft; and the dark radial markings on Aristarchus showed further developments.

Telescope: 12·6-inch clock-driven Calver equatorial.

Mr J. Evershed's Observatory, Ewhurst, Surrey

Photographs have been obtained with the liquid prism spectrograph of the great sunspot in 1946 January and February. These show interesting details of the magnetic effect in different parts of the spot.

With the same spectrograph, but substituting α-bromo-naphthalene for ethyl cinnamate in one of the prisms in order to give higher dispersion in the red region, a large number of spectra of the centre of the Sun and also of the East and West limbs has been obtained and measured. These include four solar lines of iron and eight telluric oxygen

lines. Assuming the oxygen lines to be constant in wave-length, the measures indicate small changes in the solar lines both at the centre of the Sun and at the limb, as was found for the D lines of sodium. There is also strong evidence both at the centre and limb of a progressive diminution of wave-length, as compared with my measures made in the year 1940, and with the standard solar wave-lengths published in the *Transactions of the International Astronomical Union* of 1928.

Mr M. B. B. Heath's Observatory, Kingsteignton, Devon

Mercury was observed in daylight on 26 days and 6 drawings made. Venus was observed in daylight on 53 days and 5 drawings made. Mars was observed on 19 nights and 7 drawings made. Saturn was observed on 4 nights. All results were communicated to the British Astronomical Association.

Mr F. M. Holborn's Observatory, Streatham, London

In 1946 on 163 nights 2288 observations were made of variable stars and novae, and a few of planets.

Sunspot counts and records of naked-eye spots were made on 216 days.

Records were sent to the British Astronomical Association.

Mr N. F. H. Knight's Observatory, Stoneleigh, Surrey

Longitude $+0^h\ 00^m\ 56^s{\cdot}9$.
Latitude $+51°\ 21'\ 42''$.
Altitude 155 ft. (approx.).

The observation of variable stars, contributed to the British Astronomical Association Variable Star Section, forms the entire working programme, which was unavoidably suspended for the duration of the war but re-commenced towards the close of 1945. During the year 1946 a total of 1770 observations was recorded, this being made up as follows : 900 observations of 35 Long Period Variables and 815 observations of 12 Irregular Variables of different classes, all of which are on the permanent programme of the B.A.A.V.S.S.; in addition there were obtained 5 observations of 2 other stars (μ Cephei and RT Cygni) and 50 observations of the recurring nova, Nova (T) Coronae Borealis 1866, independent discovery of the new outburst of which was made on the early morning of February 9.

Among incidental phenomena noted were observations of Comet Giacobini-Zinner on three consecutive mornings in September.

Telescopes used : refractors of 5 inches (Cooke equatorial), 2 inches and $1\frac{5}{8}$ inches aperture respectively.

Mr A. M. Newbegin's Observatory, Worthing, Sussex

Observations with the spectrohelioscope were obtained on 65 days in 1946. Weather conditions were very adverse in the summer and autumn, and throughout the year very few days were really clear.

The results indicate a general rise in solar activity, especially in sunspots frequency as the following figures show :—

Prominences, mean daily frequency $=7{\cdot}83$
Sunspots, „ „ „ $=5{\cdot}73$

Solar flares were recorded in 42 groups of sunspots, mainly of intensity 1. The great flare of July 25 was missed except in its earlier stages, when an intensity 2 was recorded at $10^h\ 07^m$. Full details will be submitted to M. d'Azambuja for inclusion in the *Quarterly Bulletin on Solar Activity*.

Many movements of dark flocculi over sunspots were measured, displacements ranging from +50 km./sec. to −126 km./sec. Line-of-sight velocities were also measured in a few prominences, indicating distinct eruptive tendencies. One marked feature of the revival in solar activity was the appearance in high latitudes of very extensive dark absorption markings, some having a longitudinal length of nearly 90°.

One item remains to be recorded: with the close of the year 1946 the work of the Observatory, which has been carried on for 32 years, ceased and the whole equipment will be handed over to the Royal Observatory, Greenwich. It will eventually be re-erected and incorporated with the Solar Department at Herstmonceux, Sussex.

Mr B. M. Peek's Observatory, Solihull, Birmingham

Systematic observations of Jupiter have been continued. Owing to increasing southerly declination of the planet, the number of determinations of the longitudes of surface features fell below 1000 for the first time since 1938.

Ten occultations of stars by the Moon were recorded in 1946.

Mr F. J. Sellers's Observatory, Muswell Hill, London

The full programme of observational work on the Sun has been carried out since 1946 May, when the spectrohelioscope was again brought into operation after the war-time interruption. The Observatory and instruments have been thoroughly renovated, repainted and the instruments readjusted. The coelostat is now controlled by synchronous motor and the vibrating-slit mechanism of the spectrohelioscope is also driven from the mains. The mirrors are being rhodiumized and an achromatic objective will shortly replace the plano-convex lens now used in order to facilitate research in other parts of the spectrum.

In the meantime a summary of solar activity, for rotations 1228 to 1242, inclusive, has been communicated for publication in the *Journal of the British Astronomical Association*.

Dr W. H. Steavenson's Observatory, Cambridge

Observations were made on 96 nights during the year. With the 30-inch Hindle reflector the programme of photometric observations of faint novae has been continued, and the results for 1945–46 have been communicated to the Society. The comets Timmers, Pajdusakova and Giacobini-Zinner were observed for position on several nights, the measures being communicated to the Comet Section of the British Astronomical Association.

Mr H. P. Wilkins's Observatory, Barnehurst, Kent

Observations of the lunar surface features have been continued with the $12\frac{1}{2}$-inch and 6-inch reflectors. The tenth Memoir of the Lunar Section of the British Astronomical Association has been prepared and awaits publication. A new map of the Moon in 25 sections on a scale of 100 inches to the Moon's diameter was published in August and a second edition in 1947 January.

REPORTS ON THE PROGRESS OF ASTRONOMY

THE CONSTITUTION OF THE PLANETS

The great cosmographer, Alexander von Humboldt, recognized among the members of the solar system three groups, to which he referred as inner, central and outer planets. In current terms, they are the terrestrial, minor and giant planets, respectively. It would seem that Humboldt regarded this classification as original. At any rate, he failed to ascribe it to some predecessor, though he meticulously recorded, in the voluminous notes appended to the celebrated " Cosmos ", the growth of the leading ideas around which his conception of the physical universe had crystallized. Humboldt's prime concern was the stark fact of nature, that residue of scientific analysis which has defied comprehension by a general law. Thus he only outlines the triumphs of gravitational astronomy, but deliberately dwells upon every known detail of the physical individuality of the celestial bodies. Humboldt insists on the remarkable disparity of the terrestrial and giant planets, especially the wide difference in density between the members of these two groups. Moreover, he notes that there exists a parallel difference in the internal density distribution, revealed by the different degree of oblateness, and with mounting warmth he speaks of the fascination these observations hold for their undeniable, if obscure, cosmogonic implications. Indeed, to Humboldt the very task of cosmography was to portray the diffuse and often elusive traits of the cosmic panorama from which he expected its history would one day be deciphered. But he clearly preferred collating facts to theorizing about them. This attitude may explain why the " Cosmos " passes lightly over the familiar hypotheses of Kant, Buffon, and Laplace.

One hundred years after the publication of the " Cosmos ", the soundness of this instinct is more patent than ever. The rational explanation of the origin of the solar system is still unaccomplished, and recent speculation has often disregarded the cosmogonic hints the present constitution of the planets might have to offer. If undertaken as an approach to the cosmogonic problem a survey of our knowledge of the planets may well leave aside many interesting results accrued from photometric, radiometric and spectroscopic investigations ; for they concern only the characteristics of an extremely thin rind, whose mass is quite insignificant. Our rather limited knowledge of the bulk properties of the planets is summarized in the first section of this review. In the next section, these few precise data are examined in relation to the theory of stellar constitution. The third section comprises a variety of speculations closely allied to the doctrines of geochemistry, and the arguments presented are largely of semi-quantitative or merely qualitative character. A brief final section epitomizes certain features of planetary constitution which appear to be of cosmogonic interest.

I. *Empirical Characteristics of the Planets*

The dimensions and masses of the planets are the most important observational data bearing upon their internal constitution. The uncertainty about the precise values of several of these quantities is fortunately of no great consequence for our discussion. Among the data listed in Table I, however, two deserve brief comment. The mean density of Neptune, the highest among the giant planets, would be reduced to about

that of Jupiter if the micrometric radius were increased by 0″·1; a systematic error of this order of magnitude does not seem impossible, considering the minuteness of the disk and the strong limb darkening caused by the heavy methane bands. The very low mean density of Mercury, comparable to that of the granitic rocks, may well be spurious. Therefore Jeffreys has suggested that it might be preferable to compute the mass of Mercury from the better known radius and an assumed law of internal density distribution (see Section II). This proposal recalls the procedure employed by astronomers up to Laplace, namely, appealing to Newton's hypothetical principle that the mean densities of the planets are inversely proportional to their mean distance from the Sun, and then finding the mass from this assumed density and the apparent volume. No mention is made, in Table I, of Pluto because so little is known about this body, except that its mass puts it into the class of the terrestrial planets.

TABLE I

Mechanical Data of the Planets

	a	M	g	V	$\bar{\rho}$	C/Ma^2
Moon	0·273	0·01226	0·1645	0·212	3·33	0·397
Mercury	0·403	0·034	0·2093	0·290	2·86	...
Venus	0·989	0·820	0·8383	0·910	4·86	...
Earth	1·000	1·000	1·000	1·000	5·52	0·3345
Mars	0·538	0·081	0·3717	0·447	3·84	0·359
Jupiter	11·26	317·1	2·501	5·32	1·30	
Saturn	9·45	95·02	1·064	3·17	0·69	0·24
Uranus	4·19	14·74	0·840	1·88	1·10	
Neptune	3·89	17·27	1·141	2·12	1·62	

a equatorial radius, unit 6278·388 km.
M mass, unit $5{\cdot}966 \times 10^{27}$ g.
g acceleration of gravity, unit 980·60 cm. sec.$^{-2}$.
V velocity of escape, unit 11·188 km. sec.$^{-1}$.
$\bar{\rho}$ mean density, unit 1 g. cm.$^{-3}$.
C greatest moment of inertia.

The greatest moment of inertia, C, of a planet can be computed from its oblateness on the Radau-Darwin theory of the ellipticity of the Earth.* For a homogeneous body the dimensionless quantity, C/Ma^2, has the maximum value, 2/5. The values of C/Ma^2 given in Table I for the terrestrial planets have been taken from H. Jeffreys †; they correspond to his models of these bodies which will be discussed in Section II. The other values have been calculated from the dynamical ellipticities of the giant planets determined by N. Lvoff.‡ Since the deviations of the individual values from Lvoff's mean, 0·24, are not well established at present, only this mean will be used in the further discussions; but there is evidence that the quantity C/Ma^2 is decidedly less for Saturn than for Jupiter.

Additional information about the interior of the Earth has been obtained by the analysis of the travel time of seismic disturbances. Since the physical principles involved have been described in concise, non-technical form§, it may suffice to draw attention to a single point. The analysis of seismic observations leads directly to the knowledge of the speed of compressional and distortional waves as function of the

* G. H. Darwin, *M.N.*, **60**, 82, 1900; H. Jeffreys, *M.N.*, **84**, 534, 1924.
† H. Jeffreys, *M.N., Geophys. Suppl.*, **4**, 62, 1940.
‡ N. Lvoff, *Russ. Astr. J.*, **9**, 68, 1932.
§ R. Stoneley, *Occasional Notes R.A.S.*, **1**, 103, 1940.

depth below the Earth's surface. Now, these speeds are commonly held to indicate both gradual changes and marked discontinuities of the internal density. It is this *interpretation* of the seismic data which has recently been criticized by two Swiss scientists, W. Kuhn and A. Rittmann, who advocate the concept of a homogeneous interior of the Earth and, in particular, deny the existence of an iron core. Their arguments will be reviewed, in Section III, in the context of rival geochemical speculations.

The surface temperatures of the planets appear to be maintained solely by the flux of solar radiation prevailing at the respective distances, but the well-known green-house effect of the atmosphere will in some cases raise the local temperatures above the black-sphere temperatures. Radiometric measurements have not revealed any appreciable heat flux from the interior. Of course, its absence does not exclude the existence of fairly high central temperatures. But for the fluid outer layers, which by convective exchange have been in continual thermal communication with a deeper solid crust, the adiabatic temperature gradient provides an estimate of the upper limit to the temperature. The internal temperatures of the planets may reach several thousands of degrees, but all the numerical values mentioned in the geophysical literature are hardly more than guesses.

Likewise, visual inspection and spectroscopic analysis * of the surfaces of the planets can tell little about the chemistry of their bulk. However, the principal chemical differences between the atmospheres of the terrestrial and the giant planets, namely, the prevalence of hydrogen compounds in the latter, can qualitatively be understood as a consequence of an enormous surplus of hydrogen, which was prevented from escaping into space by the greater surface gravity on the giant planets.† Moreover, this view of the atmospheric constitution of the giant planets is in good accord with their low mean densities, as was first pointed out by F. R. Moulton.‡

There has been a general belief that satellites could not retain atmospheres, until methane absorption was discovered in the spectrum of Titan.§ Though Titan's atmosphere is stable under present conditions, its existence would be endangered if its temperature were raised by only one hundred degrees centigrade. Consequently, if Titan's evolution passed through a stage of high surface temperature, as is widely assumed to be true of all members of the solar system, it follows that Titan's atmosphere was formed subsequently to that period. Kuiper believes that the same argument applies, with almost equal force, to Mars, and perhaps, even to Venus and the Earth. The existence of methane on Titan suggests, as Kuiper pointed out, a genetic relation to its primary, or to the other giant planets, and definitely shows that Titan cannot be a product of capture from an elliptical orbit extending into the interior region of the solar system. The mean density of Titan is almost the same as that of the Moon, and the densities of most of the satellites appear to be of the same order of magnitude. However, the densities of Rhea, Dione, Thetys, and Enceladus can little, if at all, exceed that of Saturn.‖ G. Struve arrived at the same conclusion ¶ and stressed its cosmogonic import.

* N. T. Bobrovnikoff, *Rev. Mod. Phys.*, **16**, 271, 1944.

† H. N. Russell, *Science*, **81**, 1, 1935.

‡ F. R. Moulton, *Ap. J.*, **22**, 176, 1905; see also *Introduction to Astronomy*, p. 485, New York, 1906.

§ G. P. Kuiper, *Ap. J.*, **100**, 378, 1944.

‖ P. H. Hepburn, *J.B.A.A.*, **33**, 244, 1923.

¶ *Veröff. Sternw. Babelsberg*, **6**, No. 4, 1930.

II. *Planets and the Theory of Stellar Constitution*

The theory of stellar constitution owes part of its present perfection to the circumstance that matter is highly ionized in the hot stellar interior and, therefore, obeys the laws of ideal gases. Thus the chemical composition enters only weakly into the system of equations determining the equilibrium configurations, namely, by way of the mean molecular weight and the opacity of stellar matter. But the planets, on the scale of cosmic temperatures, rank among the cold bodies, though their unknown central temperatures may reach several thousands of degrees. Consequently, the theory of planetary constitution is inextricably bound up with the complicated behaviour of matter at low temperatures. True, for pure compounds there is now available a substantial body of experimental information * and the beginnings of a quantum mechanical theory of the condensed, i. e. liquid and solid, state. But the behaviour of mixtures of several chemical compounds shows many complex and often erratic features. Though the embarrassing diversity of these phenomena admits of some classification on the principles of the theory of phase equilibria, chemical thermodynamics does not offer any detailed predictions for the state of matter inside the planets. Some of the geochemical aspects of planetary constitution will be discussed later on. The present section will deal with rather general considerations which involve a minimum of assumptions about the chemical composition. A comprehensive review † of the behaviour of matter under extreme pressures and temperatures may be mentioned here in passing.

Integral Theorems on the Internal Pressure and Temperature.—Integral theorems on the equilibrium of *gaseous* stars have been considered by Ritter, Eddington, Milne and Chandrasekhar, who has summarized these investigations.‡ Their application to the internal constitution of *non-gaseous* planets is justified provided that the bulk of the planetary matter does not have sufficient strength to support tangential stresses. In other words, hydrostatic equilibrium is supposed to exist. On the sole further assumption that the mean density $\rho(r)$, interior to a given point r, inside a spherical configuration of mass M and radius R does not increase outward from the centre, the following two theorems are available.

If G is the gravitational constant, ρ_c the density at the centre of the configuration, and $\bar{P}$ the mean pressure defined by

$$\bar{P} = \frac{1}{M}\int_0^R P dM(r),$$

where $M(r)$ denotes the mass inside r, then the first theorem states

$$\frac{3}{20\pi}\frac{GM^2}{R^4} \leqslant \bar{P} \leqslant \frac{1}{5}\left(\frac{4\pi}{3}\right)^{\frac{1}{3}} GM^{\frac{2}{3}}\rho_c^{\frac{4}{3}}. \tag{1}$$

This expression can be given a more symmetrical form by introducing the mean density of the entire configuration, $\bar{\rho} = 4\pi M/3R^3$, and substituting it on the left side of (1), viz.,

$$\frac{1}{5}\left(\frac{4\pi}{3}\right)^{\frac{1}{3}} GM^{\frac{2}{3}}\bar{\rho}^{\frac{4}{3}} \leqslant \bar{P} \leqslant \frac{1}{5}\left(\frac{4\pi}{3}\right)^{\frac{1}{3}} GM\ \rho_c^{\frac{4}{3}}. \tag{2}$$

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* See, for instance, P. W. Bridgman, *Rev. Mod. Phys.*, **17**, 3, 1945; and **18**, 1, 1946.

† F. Hund, *Ergebn. exakt. Naturw.*, **15**, 1938.

‡ S. Chandrasekhar, *An Introduction to the Study of Stellar Structure*, chapter 3, Chicago, 1939.

The second theorem concerns P_c, the pressure at the centre of the configuration:

$$\frac{3}{8\pi}\cdot\frac{GM^2}{R^4}\leqslant P_c\leqslant\frac{1}{2}\left(\frac{4\pi}{3}\right)^{\frac{1}{3}}GM^{\frac{2}{3}}\rho_c^{\frac{4}{3}}, \tag{3}$$

or

$$\frac{1}{2}\left(\frac{4\pi}{3}\right)^{\frac{1}{3}}GM^{\frac{2}{3}}\bar{\rho}^{\frac{4}{3}}\leqslant P_c\leqslant\frac{1}{2}\left(\frac{4\pi}{3}\right)^{\frac{1}{3}}GM^{\frac{2}{3}}\rho_c^{\frac{4}{3}}. \tag{4}$$

TABLE II

Lower Limits to Internal Pressures and Temperatures

	$\bar{P}$	P_c	$\bar{T}$	T_c
Mercury	$2{\cdot}3\times10^4$ atm.	$7{\cdot}3\times10^4$ atm.	125° K.	200° K.
Venus	$4{\cdot}76\times10^5$	$1{\cdot}17\times10^6$	1240	1990
Earth	$6{\cdot}76\times10^5$	$1{\cdot}66\times10^6$	1500	2400
Mars	$5{\cdot}4\times10^4$	$1{\cdot}30\times10^5$	225	1360
Jupiter	$4{\cdot}13\times10^6$	$1{\cdot}04\times10^7$	42500	67600
Saturn	$7{\cdot}66\times10^5$	$1{\cdot}88\times10^6$	15800	24400
Uranus	$4{\cdot}76\times10^5$	$1{\cdot}17\times10^6$	5275	8440
Neptune	$8{\cdot}71\times10^5$	$2{\cdot}16\times10^6$	6660	10650

The lower limits of $\bar{P}$ and P_c, according to the left halves of (2) and (3), are given in Table II. An upper limit to the central pressure would follow from the right half of (3) and (4), written in the form

$$P_c\rho_c^{-\frac{4}{3}}\leqslant\frac{1}{2}\left(\frac{4\pi}{3}\right)^{\frac{1}{3}}GM^{\frac{2}{3}} \tag{5}$$

if the equation of state, $P=F(\rho)$, were known for the hypothetical material at the centre, say metallic iron, so that ρ could be eliminated from (5). However, the central pressures nearly all exceed the experimentally accessible range, which so far has not been extended beyond 10^5 atmospheres. The theoretical equations of state proposed by Jensen * and Kothari † are of little avail for this purpose; in fact they are known to be seriously in error at pressures less than 10^7 atmospheres, because of the rather severe approximations on which the current theory of pressure ionization is based.

On the further assumption that the stellar material obeys the ideal gas law, integral theorems concerning the internal temperatures have been enunciated ‡, namely,

$$\bar{T}\geqslant\frac{1}{5}\cdot\frac{\mu m_H}{k}\cdot\frac{GM}{R} \tag{6}$$

and

$$T_c\geqslant0{\cdot}320\,\frac{\mu m_H}{k}\cdot\frac{GM}{R}, \tag{7}$$

where T_c is the central temperature and $\bar{T}$ the average temperature defined by

$$\bar{T}=\frac{1}{M}\int_0^R T\,dM(r). \tag{8}$$

Moreover, k is the Boltzmann constant, μ the molecular weight on the chemical scale, and m_H the corresponding mass unit ($1{\cdot}66\times10^{-24}$ g.). The lower limit (7) applies to configurations of sufficiently small mass so that the radiation pressure can be neglected.

* H. Jensen, *Z. Phys.*, **111**, 373, 1938.
† D. Kothari, *Proc. Roy. Soc.*, A, **165**, 486, 1938.
‡ S. Chandrasekhar, *op. cit.*, and *M.N.*, **99**, 673, 1939.

Limiting temperatures computed from (6) and (7) with $\mu = 1$ are also given in Table II. These figures are instructive, though it is not suggested that the application of the ideal gas law to the interior of the planets is legitimate. Of course, theorems of the form (6) and (7), possibly with slightly different constants of proportionality, would likewise be valid for planets composed of any matter having an equation of state $P \propto \rho$. Such is quite incompatible with the observed compressibility of matter inside the Earth, as deduced from seismic data. Therefore, the temperatures listed in Table II are clearly fictitious for the Earth and, by analogy, probably also for the other terrestrial planets. Because some astronomers still appear to cling to the conception of Jupiter and Saturn as gaseous globes, the high internal temperatures of the giant planets following from (6) and (7) are of some interest.

In fact, as recently as 1933, N. Lvoff claimed to have found a weighty argument in favour of the gaseous constitution of the giant planets.* He starts with the assumption that the internal density distribution of these bodies may be represented by an expression $\rho \propto r^{-n}$, where r is the distance from the centre, and determines the flattening as the function of r, from Clairaut's and Darwin's theory. In the first approximation he finds $n = 2{\cdot}0$ for all the planets. In the second approximation he assumes the small terms of the second order to be known (computed with $n = 2$) and determines n again, separately for each planet, with the result $n = 1{\cdot}99$, $2{\cdot}07$, $2{\cdot}04$ and $1{\cdot}96$ for Jupiter, Saturn, Uranus and Neptune, respectively. He concludes that the exponent n very closely equals 2 (the mean of the four values given being $2{\cdot}015 \pm 0{\cdot}017$) and within the limits of observational errors is identical for all the giant planets, suggesting a homologous constitution. The second statement is perhaps somewhat too optimistic, for the value of n is quite sensitive to the adopted radii and surface ellipticities. Consequently, the internal agreement would have been less impressive if other values of radii or ellipticities had been selected from the literature. It is not evident, for example, why Lvoff uses Rabe's micrometric value of the ellipticity of Jupiter, but for Saturn prefers H. Struve's dynamic value derived from the perturbations of the satellites. Quite apart from the degree of numerical agreement between the different planets, the mere emergence of the exponent $n = 2$ hardly warrants the identification of the giant planets with isothermal gaseous globes. Lvoff demonstrates that the empirically valid density law $\rho \propto r^{-n}$ implies the proportionality of pressure to density throughout the entire configuration, which indeed obtains in an ideal gas of constant temperature. But this argument disregards two physically significant points. Firstly, in the centre the assumed density law has a singularity, while $d\rho/dr$ vanishes at the centre of an isothermal gaseous sphere; moreover, the acceleration of gravity also would become infinite at the centre of Lvoff's model. Secondly, at the surface of Lvoff's model the density remains finite; but it is well known that the radius of a wholly gaseous, isothermal sphere is infinite. Thus Lvoff's argument fails to convince, and his density law cannot be accorded a higher status than that of an interpolatory expression, without any deeper physical meaning beyond the vague suggestion of a possibly "homologous" constitution of the several giant planets.

In order to give a different turn to this criticism of the gaseous nature of the giant planets, consider instead of Lvoff's physically inadmissible model a composite polytropic configuration of finite radius, consisting of an isothermal core ($n = \infty$) and a polytropic envelope ($n < 5$). The study of such composite polytropic systems, which was inaugurated by Emden, has shown that the equations of fit—expressing the continuity of pressure

* N. Lvoff, *Russ. Astr. J.*, **10**, 141, 1933.

and density at the surface of the core—impose distinct restrictions upon the size of the core. In the present context it is of interest to compare the moment of inertia of such composite systems with that of the giant planets. From the data given in Emden's book *, the following values of the moment of inertia, I, were computed for spherical configurations of mass M and radius R, having an isothermal core:

	$n=0$	$n=1$	$n=3/2$
I/MR^2	0·286	0·200	0·147

Here n is the polytropic index assumed to be constant throughout the envelope. The index $n=3/2$ corresponds to the adiabatic density law of a monatomic gas; for molecules consisting of two or more atoms, the value of I/MR^2 would be much smaller than 0·15. Now the observed values of I/MR^2 are about 0·24 for the giant planets, according to Table I. This figure is much too large to admit of representation by a composite polytropic system with isothermal core. Although the giant planets are not strictly spherical configurations, their deviations from spherical symmetry can hardly invalidate the verdict just given, because the numerical discrepancy is so great. There appears to be no escape from the conclusion that the interior of the giant planets cannot resemble that of hot gaseous stars, and the long-cherished picture of Jupiter as a miniature sun has to be abandoned. The same conclusion was reached already in 1923 by H. Jeffreys.† He considered the amount of heat that any planet would have lost if its interior were in complete thermal communication with its surface, and found it enough to solidify the planet on any reasonable hypothesis concerning its original temperature. After solidification the hypothesis that there is free thermal communication from the interior to the surface breaks down. Then the surface would cool down until it was much cooler than the interior, and heat would be only slowly conducted out.

Emden analysed the structure of gaseous spheres constrained by rigid shells (see chapter 11 of *Gaskugeln*), having in mind applications to stars with a solid crust. For instance, he proved that the mass of a stellar core obeying the equation of state $P \propto \rho$ cannot exceed 77 per cent. of the total mass of the configuration, irrespective of the state of the envelope. But so far this part of Emden's work has not been put to use in interpreting the final stage of planetary evolution.

Planets and Degenerate Stellar Models.—In 1935 H. N. Russell pointed out that among the planets, i.e., *cold*, dense bodies, the radius increases with the mass, while the opposite trend prevails among the white dwarf stars. These bodies must also be regarded as *cold* stars, in the sense that the degree of ionization of their interior is independent of the temperature and is determined by the pressure alone; except for a very thin outer shell of practically negligible mass, throughout which the ordinary laws of high-temperature ionization hold. Russell concluded that somewhere between the masses of the white dwarfs and the planets there ought to exist a maximum radius for stellar configurations consisting of cold matter. Proof for this conjecture was soon adduced by D. S. Kothari ‡, who found the maximum radius of a cold body to be of the order of 10^9 to 10^{10} cm., depending on the composition.

Kothari's first investigation neglected the variation inside the star of the degree of ionization, which was assumed to correspond to that existing at a constant density equal

* R. Emden, *Gaskugeln*, chapter 12, Leipzig and Berlin, 1907.
† H. Jeffreys, *M.N.*, **83**, 350, 1923.
‡ D. S. Kothari, *M.N.*, **96**, 833, 1936.

to the mean density of the configuration. Later on F. C. Auluck * removed this defect by incorporating into the analysis the theory of pressure ionization, already developed by Kothari †, but the results do not differ significantly from the previous ones. In a log M-log R-diagram all the points representing the planets and white dwarfs fall between two curves predicted for hydrogen and iron, respectively; for the theory has so far been worked out only for configurations composed of a single species of atoms. Essentially the same picture again resulted when P. Sen ‡ developed the analogue of Kothari's theory for simple molecules, like CH_4, NH_3 and H_2O. Evidently, the planetary radii predicted from this type of theory of the solid body are rather insensitive to the stipulated chemical composition. On Kothari's and Auluck's diagrams the terrestrial planets trace a line of nearly constant density, which runs quite close to the line of " iron planets ". This approximate coincidence must not be taken as implicit evidence for the existence of large iron cores in these bodies, because the boundary curve characteristic of the iron planets has been obtained by a somewhat arbitrary adjustment, which will be described presently. In fact, when extrapolated to the pressure of one atmosphere, Kothari's equation of state gives for all elements densities far in excess of the observed ones. In order to mitigate this shortcoming of the theory, Kothari and Auluck have appealed to experience and changed a certain parameter, ρ^*, in the equation of state, which signifies the density of the element at a pressure producing single ionization on the average. Thus, instead of using for iron $\rho^* = 69{\cdot}9$ g. cm.$^{-3}$, a value that follows " naturally " from the theory, they have adopted $\rho^* = 7{\cdot}86$ g. cm.^{3}, since the density in the singly ionized state can obviously not differ much from that of the normal metal. The radii of the iron planets predicted without this adjustment would be smaller, by a factor $7{\cdot}86/69{\cdot}9$, than the published ones; and the close coincidence of the line defined by the terrestrial planets with the boundary curve for iron would disappear.

Now it is doubtless unfair to the theory of pressure ionization to compare the natural value of ρ^* with the density of the normal metal, since the assumptions made in theory render it particularly inaccurate in the region of low ionization. On the other hand, in the present stage the theory cannot yield any new information concerning the internal constitution of the planets. A. Sommerfeld || has modified Kothari's analysis in one respect; instead of assuming constant electron density inside the atom, he used the density distribution according to the Thomas-Fermi model of the atom. The ensuing change in the appearance of the log R-log M-diagram is marked. The maximum radius still lies between 10^{-2} and 10^{-3} solar radii; but the maximum is poorly defined, as the boundary curves for hydrogen and iron planets have a much smaller inclination against the log M-axis than in Kothari's diagram. The iron curve now runs above the symbols of the terrestrial planets, though the giant planets still fall between the iron and hydrogen curves. Sommerfeld himself has expressed doubt as to whether his approach to the problem constitutes a significant improvement on Kothari's analysis; because such could be expected only if the Thomas-Fermi theory would be applied not to the individual atom but to the solid body as a whole.

It would seem then that the chief merit of Kothari's theory is to have linked, in a general way, the theory of planetary constitution to that of degenerate stellar configurations. Although the verifiable consequences of the theory do not afford a deeper insight into

* F. C. Auluck, *M.N.*, **99**, 239, 1939.
† D. S. Kothari, *Proc. Roy. Soc.* A, **165**, 486, 1938.
‡ P. Sen, *Z. Astrophys.*, **16**, 297, 1938.
|| A. Sommerfeld, *Nuovo Cim.*, **15**, No. 1, 1938.

the nature of the bodies of the solar system, the theory has a distinct bearing upon such planet-like companions of double stars as were recently discovered by K. Aa. Strand (61 Cygni) and by D. Reuyl and E. Holmberg (70 Ophiuchi). These unseen companions have masses of the order of one hundredth of that of the Sun, or not much more than 10 times the mass of Jupiter. It is not certain that the matter inside these stars is really "cold", but on this extreme assumption Kothari's theory furnishes a minimum radius for these bodies. Russell * has shown that any body exceeding 1/300 of the Sun's mass must, before it contracts to the cold and partially degenerate state, pass through a stage in which the greater part of its mass consists of highly ionized gas. Despite central temperatures of about one million degrees, the low surface temperature in this stage may render the star invisible by its own light.† However, if revolving around a main-sequence star, such body should reflect amounts of light comparable with the major planets of the solar system. Therefore Russell ‡ has urged that it is well within the bounds of accepted usage to call these new bodies planets.

Special Planetary Models.—The ideally gaseous and wholly degenerate models of the planets, which appeared attractive for the simplicity of the respective equations of state, have proved inadequate. Any attempt to devise more concrete planetary models is open to criticism because there is so little precise information about the chemical nature of the bulk of the planets. Moreover, it is difficult to put a stringent test to any particular hypothesis concerning the chemical composition, for lack of observational data other than the mean densities and moments of inertia of the planets. In the case of Jupiter and Saturn, with their marked increase in density toward the centre, there is perhaps some hope of obtaining in the future additional information about the density distribution from the terms of higher order in the potential affecting the satellite motions. Jupiter's fifth satellite would seem to offer the best chances, but the effect is very small at any rate.§ The prospects are rather poor for Saturn, because of the unknown influence of the ring system on the orbits of the inner satellites. For the time being, then, all that can be done is to represent quantitatively the observed mean density and moment of inertia on plausible assumptions concerning the interior composition and the compressibility of planetary matter. The interior of the Earth has been commonly pictured, since the turn of the century, as a succession of concentric shells of increasing density, surrounding a heavy metallic core, and the same general picture also dominated speculation on the interior of the other planets. Although this view has recently been challenged, it will be convenient to defer discussion of the novel conception of a homogeneous interior of the planets, and to report first on the investigations based on the conventional view of planetary constitution.

As the simplest case, consider a two-phase spherical configuration of mass M and radius R. At the fraction x of the radius, let a surface of discontinuity separate a shell of uniform density ρ_1 from a core of uniform density ρ_2. The moment of inertia of this configuration is given by

$$I = \frac{8\pi}{3}\left[\int_0^{xR} \rho_2 r^4 dr + \int_{xR}^{R} \rho_1 r^4 dr\right] = \frac{8\pi}{15} R^5[(\rho_2 - \rho_1)x^5 + \rho_1] \qquad (9)$$

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* H. N. Russell, *A.J.*, **51**, 13, 1946.
† H. Babcock, *P.A.S.P.*, **55**, 149, 1943.
‡ H. N. Russell, *P.A.S.P.*, **55**, 79, 1943.
§ D. Brouwer, *A.J.*, **51**, 223, 1946; W. de Sitter, *Ann. Sternw. Leiden*, **12**, Part I, 48, 1918.

and the mass by

$$M=\frac{4\pi}{3}R^3\bar{\rho}=\frac{4\pi}{3}R^3[(\rho_2-\rho_1)x^3+\rho_1]. \tag{10}$$

Hence

$$\frac{I}{MR^2}=\frac{2}{5}\cdot\frac{1}{\bar{\rho}}[(\rho_2-\rho_1)x^5+\rho_1].$$

After introducing the abbreviations

$$\alpha=\frac{\rho_1}{\bar{\rho}} \quad \text{and} \quad \beta=\frac{\rho_2-\rho_1}{\bar{\rho}} \tag{11}$$

the following conditions are found from equations (9) and (10)

$$\alpha+\beta x^3=1.$$
$$\alpha+\beta x^5=\frac{5}{2}\cdot\frac{I}{MR^2} \tag{12}$$

from which α and β can be determined if x is known:

$$\alpha=1-\left[1-\frac{5}{2}\frac{I}{MR^2}\right]\frac{1}{1-x^2}, \qquad \beta=\left[1-\frac{5}{2}\frac{I}{MR^2}\right]\frac{1}{x^3-x^5}. \tag{13}$$

The mean densities of shell ρ_1 and core ρ_2, then follow from equations (11).

On this mathematical model, E. W. Wiechert in 1897 based the first modern physical model of the Earth, a dense core surrounded by a lighter mantle. Up to that time, astronomers had considered only fictitious density laws, arbitrarily chosen to allow the ellipticity equation to be integrated in finite terms. Thus Laplace and Roche assumed continuous density distributions which, however, disagree with what is now known about the compressibility of matter in the interior. The failure of both "laws" is evident from their wrong prediction of the surface density of the Earth. According to equations (13), the densities of core and mantle are 12·04 and 4·27 g. cm.$^{-3}$ respectively, when we take x from Gutenberg's modern value (2900 km.) for the depth of the great discontinuity. The densities actually obtained by Wiechert were somewhat smaller, but still large enough to permit the suggestion, apparently originated by Wiechert, that the Earth has a metallic core, consisting mainly of iron. All subsequent work on the density distribution inside the Earth is essentially a refinement of Wiechert's model, incorporating what has since become known about the compressibility of the siliceous mantle and the iron core, and fitting into the picture the other discontinuities discovered by later seismological exploration. A detailed report on these investigations is outside the scope of this review, but some references * to recent work are given below. H. Jeffreys † applied these geophysical results to the other terrestrial planets, mainly in order to test Bernal's hypothesis that a change in density about 470 km. deep in the Earth represents the transition of olivine to a denser high-pressure modification of cubic crystal form.‡ This hypothesis was found to agree well with the data for the Moon, while the alternate hypothesis that the 470 km.-discontinuity is due to a new material fails. Bernal's hypothesis does not by itself explain the density of Mars, but agreement

* K. E. Bullen, *Bull. seism. Soc. Amer.*, **30**, 235, 1940 and **32**, 19, 1942 ; R. A. Daly, *Bull. geol. Soc. Amer.*, **54**, 401, 1943 and **57**, 707, 1946.

† H. Jeffreys, *M.N., Geophys. Suppl.*, **4**, 62, 1940.

‡ J. D. Bernal, *Observatory*, **59**, 268, 1936.

can be obtained if Mars has a small central core similar to that of the Earth. The alternative hypothesis of a new material would also fit the data for Mars, but the amount of it is much larger than the Moon's density would suggest. Bernal's hypothesis gives, on the assumption of hydrostatic equilibrium, an ellipticity for Mars rather greater than the observed value, the alternative one rather less; but the differences are no more than one should expect from the loads known to be supported by the strengths of the Earth and Moon. Jeffreys also obtained a solution for Venus, but it does not seem to lead to any verifiable inferences. In the case of Mercury, there is great uncertainty about its mass. Therefore Jeffreys reversed the procedure and computed the mean density, using Bernal's hypothesis, from the better known diameter of the planet; the results are $\bar{\rho}=3{\cdot}39$ g. cm.$^{-3}$, $M=M\odot/9\ 120\ 000\ (1\pm 0{\cdot}084)$. If Mercury has a small dense core, these figures may have to be increased by a few per cent. The same general idea underlies G. H. Hill's estimate of the mass of Mercury * from Laplace's law for the internal density. To sum up, the internal constitution of the terrestrial planets can be readily interpreted on the model of the Earth that emerged from geophysical investigations. Venus and Mars appear to have a dense core like the Earth, but such is definitely absent in the Moon and, at best, quite small in Mercury.

The giant planets must have a strikingly different constitution because of their low mean densities and strong concentration of density toward the centre. As a first approximation, their internal density distribution may be interpreted by the spherical two-phase model described above. Since the radius x of the surface of discontinuity is unknown, it must be treated as a free parameter. The equations (12) have been solved with $I/MR^2=0{\cdot}24$, according to Table I, and the results are plotted in the figure as function of x. The value of I/MR^2 is identical, within the limits of observation, for all the giant planets. Therefore, Fig. 1 applies to all of them, since the ordinates chosen are the dimensionless quantities $\rho_1/\bar{\rho}$ and $\rho_2/\bar{\rho}$, plotted on a logarithmic scale. With α less than unity, by definition, it follows from equation (13):

$$1-x^2>1-\frac{5}{2}\frac{I}{MR^2}, \quad \text{or} \quad x\leqslant 0{\cdot}7746. \tag{14}$$

Moreover,

$$\lim_{x\to 0}\alpha=\frac{5}{2}\frac{I}{MR^2}, \quad \text{or} \quad \rho_1\leqslant 0{\cdot}60\bar{\rho} \tag{15}$$

and

$$\beta\geqslant 2{\cdot}152, \quad \text{or} \quad \rho_2\geqslant 2{\cdot}152\bar{\rho}. \tag{16}$$

After substituting $\bar{\rho}$ from Table I into the inequalities (15) and (16), the limits listed in the left half of Table III are found.

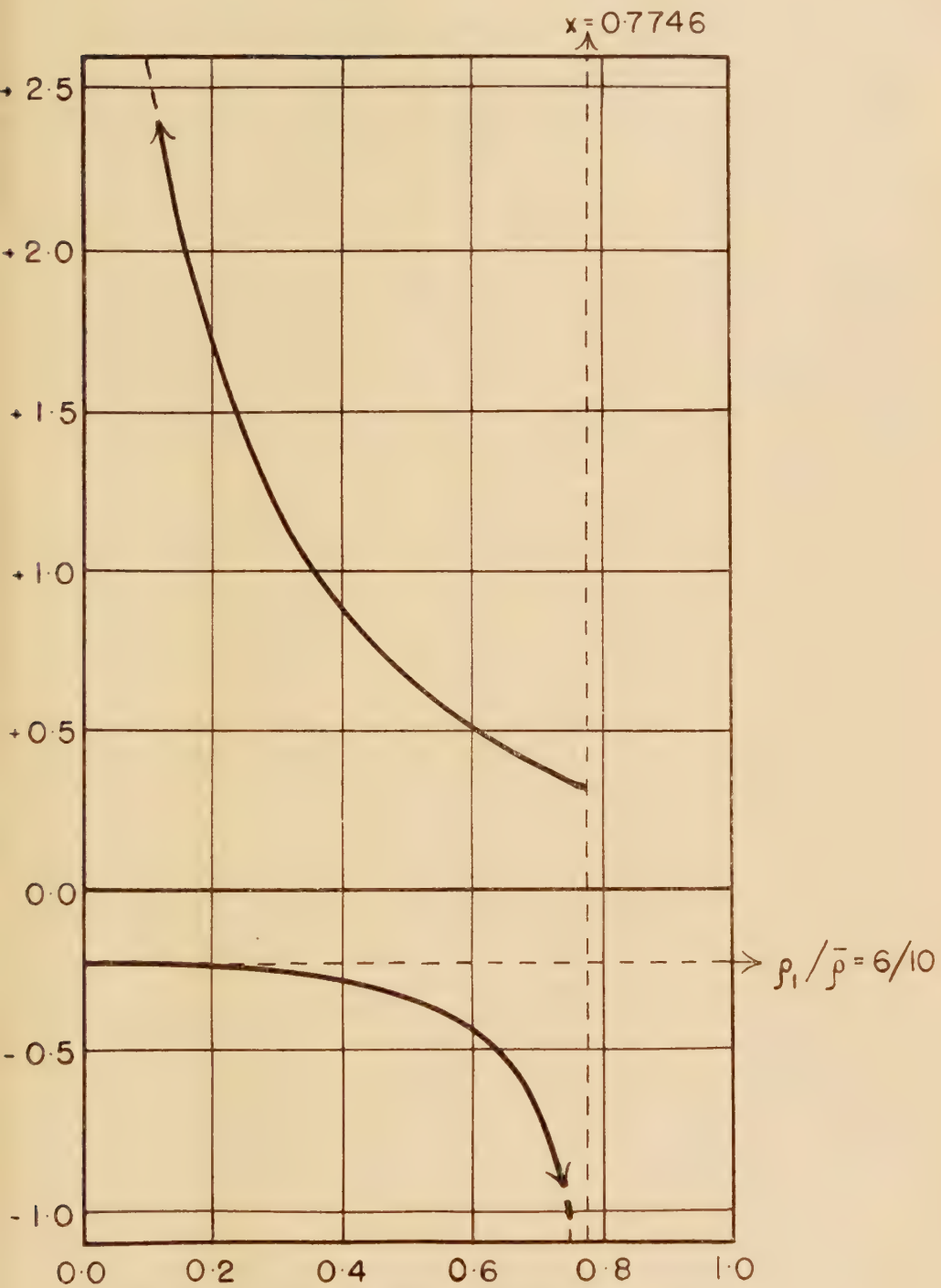
TABLE III

Two-Shell Model of the Giant Planets

	Density Limits		x	ρ_1	M_1/M_2
Jupiter	$\rho_1\leqslant 0{\cdot}78$ g. cm.$^{-3}$	$\rho_2\geqslant 2{\cdot}80$ g. cm.$^{-3}$	0·52	0·59	0·60
Saturn	0·425	1·48	0·38	0·36	1·04
Uranus	0·66	2·36	0·46	0·54	0·76
Neptune	0·96	3·44	0·56	0·68	0·53

The values of the upper limit for ρ_1 are surprisingly small, indicating that the shell must consist of some exceedingly light substance. The density of the core, ρ_2, must at least be that of terrestrial rocks, say greater than 3·0 g. cm.$^{-3}$. More likely it is of

* G. H. Hill, *A.J.*, **19**, 156, 1898.



Two-Shell Model of the Giant Planets. Abscissae: radius of discontinuity. Ordinates: $\log_{10}\rho/\bar{\rho}$. Upper curve refers to core and lower to mantle.

the order of the mean density of the Earth, or even somewhat higher, because of the higher mean pressure inside the giant planets (*cf.* Table II). Assuming ρ_2 to be 6 g. cm.$^{-3}$, the corresponding values of x and ρ_1 have been read from the accompanying figure; they are given in the right half of Table III. It is seen, then, that in all cases the actual densities of the shell must be quite close to the upper limits of (first column of Table III). The only substances known to have such low densities are the so-called permanent gases in the state of high compression, which may lead even to solidification. It is important to realize that all gases in the atmospheres of Jupiter or Saturn would be so highly compressed under their own weight, that they would assume densities of the order of ρ_1 at a depth, below the visible surface of these planets, which is less than 1 per cent of their radii.* Therefore the density appears to be practically constant throughout the mantle of the giant planets, which occupies more than 80 per cent of their volume. The last column of Table III gives the mass ratio, M_1/M_2, of shell to core corresponding to the values of x found for $\rho_2=6$ g. cm.$^{-3}$. Although the giant planets deviate markedly from spherical shape, the neglect of the oblateness can cause only minor modifications of the numerical values in Table III, and the general argument remains unaffected.

If the two-phase model just considered is replaced by one having two or more shells surrounding the core, the same upper bound (15) to the density of the outermost shell results. In the limiting case of an infinite number of shells, i.e. for a continuous distribution of density, the inequality (15) was first discovered by Jeffreys.† However, he thought that a large fraction of the volume would constitute a cloudy atmosphere of negligible mass, being unaware of the enormous compression of the atmospheric gases under their own weight. Attention to this inconsistency was first drawn by W. H. Wright ‡, and later it was also noticed by others.

To put it differently, Jeffreys' view of the nature of the outermost layer of the giant planets corresponded, in terms of the two-phase model described above, to the case of $x=0{\cdot}77$, or $\rho_1 \ll 1$. Further it was pointed out that in the outer shells of the giant planets there may be realized a variety of processes and states such as had not hitherto come under the scrutiny of geophysicists and geologists.§ One of these possibilities is the hypothetical existence of condensed hydrogen in a metallic form; the same suggestion was made simultaneously by Kothari.‖ There are a number of thermo-chemical and photochemical reasons why hydrogen should be abundant in the atmospheres of the giant planets ¶, and it may well constitute the bulk of their shell material. The heat conductivity of metallic hydrogen has been estimated by Critchfield**, who believes that it is high enough to permit the escape of any likely heat flux from the interior of Jupiter without raising the temperature above the melting-point of the crystal lattice.

Another difficult problem is posed by Jupiter's Great Red Spot, which behaves like a solid body floating in a dense fluid phase. The consequences of this hypothesis have been explored by Peek.†† He also tried to gain deeper insight into the fluid mechanics of Jupiter's atmosphere from an analysis of the motions of another transitory spot

* B. M. Peek, *M.N.*, **97**, 574, 1937.
† H. Jeffreys, *M.N.*, **84**, 534, 1924.
‡ W. H. Wright, *Lick Obs. Bull.*, **13**, 64, 1927.
§ R. Wildt, *Veröff. Univsternw. Göttingen*, No. 40, 1934 and *Ap. J.*, **87**, 508, 1938.
‖ D. S. Kothari, *Proc. Roy. Soc.*, A, **165**, 486, 1938.
¶ R. Wildt, *Nature*, **134**, 418, 1934 and *Ap. J.*, **86**, 321, 1937.
** C. L. Critchfield, *Ap. J.*, **96**, 1, 1942.
†† B. M. Peek, Presidential Address, *J.B.A.A.*, **50**, 1, 1940.

which, in 1940, appeared in Jupiter's South Temperate Belt.* There cannot be any doubt that the outer layers of Jupiter, and of Saturn, are fluid, but the depth of this fluid layer is uncertain. As a corollary to his dynamical theory of Jupiter's atmosphere, J. Wasiutýnski † has again advanced the thesis that the giant planets are fluid throughout. This claim would seem to require further substantiation, with regard to what has been said above about Lvoff's similar ideas and Jeffreys' remarks on the rate of cooling of wholly gaseous planets.

III. *Geochemical Considerations*

The task of the science of geochemistry is to determine quantitatively the chemical composition of the Earth and to ascertain the laws governing the distribution of each element throughout the globe. The recognition of geochemistry as an autonomous discipline goes back to Christian Friedrich Schönbein (1799–1868), and the first systematic exploration of this domain was undertaken by K. G. Bischof and J. Roth. During the 19th century geochemical research mainly dealt with the differentiation of the crustal material of the Earth accessible to visual inspection and chemical assay. More recently geochemical speculation has turned to the interior of the Earth and the pre-geological stages of planetary evolution, and thus has made contact with geophysics and especially seismology. Space does not permit to sketch here this trend, but reference may be made to several articles surveying the territory where geochemistry and planetary astrophysics overlap.‡

Composition of the Planetary Matrix.—Geochemical speculation has started with the *postulate* that the primitive planets were hot gaseous bodies, homogeneous throughout, and consisting of " solar matter " of unspecified composition, presumably rich in hydrogen and other light elements. The latter assumption can now be qualified according to recent astrophysical determinations of the composition of the Sun. In the photosphere the abundance ratio (by numbers of atoms) of hydrogen to the Sun of all the metals (including silicon) is of the order of 5,000–10,000.§ This result is confirmed by a recent quantitative analysis of the chromosphere.‖ The number of helium and oxygen atoms probably exceeds many times the total number of metallic atoms, but no precise determinations are possible for certain spectroscopic reasons. From the mean molecular weight of the metals it follows that they constitute less than 1 per cent. of the mass of the solar atmosphere. But in the interior of the Sun the metals are much more abundant ; the best recent values for the composition are: hydrogen 50 per cent helium 40 per cent, Russell mixture of metals 10 per cent, by weight.¶ The great abundance of hydrogen in the solar atmosphere is probably only " skin-deep ". If the planets were formed by disruption of the Sun (or a passing star), it would have been necessary to draw upon the hydrogen-poor solar interior to provide sufficient mass and, therefore, the composition of the planetary matrix must have agreed closely with that of the solar interior just given.

However, the exact composition of the primitive gaseous planet may prove of little cosmogonic consequence, because during the initial stages of evolution the rate of thermal

* B. M. Peek, *M.N.*, **101**, 70, 1941.

† J. Wasiutýnski, *Astrophys. Norvegica*, **4**, 331, 1946.

‡ R. Wildt, *Proc. Amer. phil. Soc.*, **81**, 135, 1939; *Scientia*, **34**, 85, 1940; *Rev. Mod. Phys.* **14**, 151, 1942.

§ B. Strömgren, *Festschrift für Elis Strömgren*, p. 218, Copenhagen, 1940.

‖ R. Wildt, *Ap. J.*, **105**, 36, 1947.

¶ M. Schwarzschild, *Ap. J.*, **104**, 203, 1946.

dissipation into space must have been very high. The attendant preferential loss of the lighter elements would rapidly have altered the average composition. A closer analysis of this process is greatly to be desired. As a first step toward the solution of the problem an answer to the following question is required: given a gaseous stellar configuration with a mass of planetary order, what is the rate of change of radius and surface temperature, if the radiated energy is furnished solely by contraction? For masses greater than one-tenth of the solar mass the answer is readily obtainable.* But for small masses the central temperatures of such stellar models are so low that Morse's tables of the opacity coefficient become inapplicable. Further advance along this line of cosmogonic studies must therefore await the extension of Morse's work into the low-temperature field ($T_c < 400{,}000$ deg. K.).

If the planets have been formed by a rather slow condensation from a tenuous substrate, it would have to be shown how sufficiently large masses of the light elements could have been captured. Such would be required in order to account for the low mean densities of the giant planets. This point has been given too little attention by the recent theories of planetary accretion from cold matter. Capture of light gases by hot condensation centres would seem more difficult. A related problem needs clarification: what are the central temperatures attained in an initially cold planet, either by early contraction or by later production of radioactive heat?

First Geochemical Separation of Phases.—The first stage of planetary evolution is the separation of the primitive gaseous planet into an atmosphere and a liquid core. Two attempts to analyse this process quantitatively have recently been undertaken.† The method used was to determine the points of intersection between the graph representing the radial distribution of pressure and temperature in a polytropic gaseous sphere and a second graph defining the line of co-existence of liquid and saturated vapour (equation of Clausius-Clapeyron). It appears that with masses like that of the Earth, liquefaction would start in the outer regions of the globe and only in masses of a much lower order of magnitude could initial liquefaction extend right to the centre of the configuration. Baumgartner has also studied the differential equation for a gaseous sphere which is in the state of saturation all along the radius. The prime interest of these investigations derives from their pioneering character. The specific results may be subject to modification when some of the underlying simplifications of the problem are given up. Moreover, there exist strong objections to the facile assumption that in a mixture of several elements or compounds, liquefaction must occur as soon as the partial pressure of an individual component has reached its saturation value (as measured in the pure state). In particular it has been pointed out ‡ that a mixture of 90 per cent. of hydrogen and 10 per cent of iron (" solar matter ") may well be in a hypercritical state at a temperature of, say, 5000 deg. K., so that the formation of a liquid core in a primitive planet could not occur unless its mass was so small as to let most of the hydrogen escape.

Traditional geochemical speculation has not envisaged the possibility that the primitive Earth was largely composed of hydrogen, but rather conceived of the terrestrial matter as an incompletely oxidized mixture of metals and silicon. Further cooling of the originally homogeneous liquid phase is supposed to have led to decomposition into at least three liquid phases ; namely, native metal, metallic sulphides and silicates, in

* M. H. Harrison, *Ap. J.*, **102**, 216, 1945.

† A. Mercier, *Nature*, **141**, 201, 1938 and *Arch. Sci. phys. Nat.*, **20**, 31, 1938; W. Baumgartner, *Helv. phys. Acta*, **18**, 167, 1945.

‡ W. Kuhn, *Experientia*, **2**, 391, 1946.

the order of decreasing densities. It is further assumed that these phases settled out in the internal gravitational field, so that concentric shells of differing chemical composition were formed. The details of this process have especially been studied by G. Tammann and V. M. Goldschmidt, who based their conclusions on the theory of *equilibrium* states of chemical reactions between adjacent liquid phases. This theory gives satisfactory account of the distribution of the rare elements among the several liquid phases and especially explains the relative abundance of trace elements in the metallic, sulphide and silicate phases of meteorites. In fact, the occurrence of the metallic and silicate types of meteorites was regarded as a strong argument in favour of the hypothesis that meteorites were formed by disruption of a planet which had undergone the gravitational separation just described before it solidified. The lack of wholly sulphidic meteorites can easily be explained by the high probability of complete combustion of such bodies during their flight through the Earth's atmosphere (W. A. Wahl). The existence of meteorites of the pallasite type, which are mixtures of silicates and native iron, can be explained by solidification of small bodies, whose gravitational field was not strong enough to enforce separation of phases.

A Homogeneous Earth Model.—Only a few years ago W. Kuhn and A. Rittmann advanced a radically different hypothesis concerning the interior of the Earth, whose acceptance would have far-reaching geochemical consequences.* At the outset it should be emphasized that the authors of the new theory do not have at their disposal new observational information about the Earth's interior, but rather are concerned with the interpretation of well-known data and their speculative extrapolation. Kuhn and Rittmann's views have been critically analysed by several scientists †, but none of these papers have been accessible to the reviewer. Communication difficulties during wartime have impeded free discussion and, therefore, the new theory is still *sub judice*. It is particularly to be regretted that none of the leading geophysicists has so far examined its seismological implications. J. Geszti ‡ appears to have anticipated some of Kuhn and Rittmann's ideas, but his published work deals mainly with special problems of geodynamics.

Briefly, Kuhn and Rittmann suggest that the Earth consists of a thin solid crust, a shallow magmatic zone of molten silicates underneath, and otherwise of practically unchanged "solar matter", rich in hydrogen. The concept of a metallic core is explicitly rejected, and nowhere are material discontinuities supposed to exist. The chief argument for the chemical homogeneity of the interior is its high viscosity, which, it is claimed, would have prevented gravitational separation of non-miscible phases even during periods of the order of 10^9 years. In other words, Kuhn and Rittmann do not dispute the tendency toward decomposition predicted by chemical thermodynamics, on which conventional geochemical speculation relied; in fact differentiation did occur throughout the magmatic mantle, whose formation resulted from partial degassing of the solar matter. But the authors insist that the geological time-scale is too short to have permitted a realization of mechanical and chemical equilibrium in a body the size of the Earth. However, Kuhn estimates that complete gravitational

* W. Kuhn and A. Rittmann, *Geol. Rdsch.*, **32**, 215, 1941; W. Kuhn, *Naturwissenschaften*, **30**, 689, 1942 and *Experientia*, **2**, 391, 1946.

† A. Eucken, *Naturwissenschaften*, **32**, 112, 1944 and *Nachr. Akad. Wiss. Göttingen, Math.-Phys. Kl.*, **1944**, Heft 1; H. Haalk, *Z. Geophys.*, **18**, 32, 1943; P. Eskola, *S.B. finn. Akad. Wiss.*, **1945**, 219, 1945.

‡ J. Geszti, *Beit. Geophys.*, **49**, 26, 1937

separation into a silicate mantle and an iron core may have been attained in bodies of a few hundred kilometres diameter during the course of a few weeks. The entire argument proceeds on the tacit assumption that the Earth already had its present dimensions when the internal temperature dropped to a point at which the homogeneous melt began to decompose. One naturally wonders if rapid separation of phases was not possible during much earlier time when the Earth had, say, 10 times its present diameter. At this point it becomes apparent how important are further investigations on the liquefaction of gaseous planets, which would substantiate and extend the work of Mercier and Baumgartner mentioned before.

If this argument for an essentially homogeneous interior of the Earth be accepted, we still would have to account for the variation with depth of the speed of seismic waves, and especially for the disappearance of the distortional waves at a depth of 2900 km. The explanation urged by Kuhn and Rittmann makes use of the concept of relaxation time, τ, of a viscous medium. This quantity is proportional to the viscosity, η, the coefficient of proportionality being the reciprocal of the torsion modulus, μ; hence, $\tau=\eta/\mu$. The relaxation time is a measure of the rate at which tangential stresses die out due to an elastic flow. Against disturbances having periods small compared with τ, the medium will essentially behave as if rigid, while toward those having periods long compared with τ it will display a fluid character. Thus it becomes necessary to assume that the relaxation time inside the Earth decreases continuously with depth, and reaches a value of the order of 10 sec. at a depth of 2900 km. (the critical level at which the distorsional waves seem to disappear); at a depth of 1000 km., τ is estimated to be about 10^9 sec. Just how this enormous decrease of the relaxation time comes to pass is not sufficiently clear. The viscosity is known to rise enormously with the pressure, and to decrease less rapidly with the temperature. In the Earth, it is suggested, the increase of η with pressure is overcompensated by the higher temperatures at great depth and the increasing content of hydrogen dissolved in the "solar matter". According to Kuhn and Rittmann, volcanological experience teaches that the viscosity, and hence also the relaxation time, of magmatic melts is greatly reduced by dissolved gases and other volatile components. Since the torsion modulus is not very sensitive to compression or much dependent on the composition of matter, the authors conclude that the relaxation time is roughly proportional to the viscosity. The required rapid decrease of the viscosity at the critical depth, at any rate, is difficult to justify. This is probably the most vulnerable point of the new theory, and the authors do not claim that their case can be proven quantitatively. To strengthen this weak link in the chain of reasoning, R. Kronig and J. D. van der Waals have appealed to the behaviour of hydrogen under high pressure. As pointed out before, hydrogen changes, on sufficient compression, from a molecular to an atomic phase. This sudden transition, according to a recent computation by Kronig, de Boer and Korringa *, occurs at a pressure of 7×10^5 atmospheres and entails a jump of the density from 0·4 to 0·8 g. cm.$^{-3}$. The Dutch physicists now propose to identify the depth of 2900 km. with the region where the partial pressure of hydrogen reaches the critical value of 7×10^5 atmospheres. Moreover, they take the two adjacent phases of hydrogen to be "loaded" with heavier atoms, dispersed in such concentration among the molecules and atoms as to give the resultant density the value of 8 g. cm.$^{-3}$, estimated by Kuhn and Rittmann for this depth. This density would imply a hydrogen content of the order of 10 per cent by weight in

* R. Kronig, J. de Boer and J. Korringa, *Physica*, **12**, 245, 1946.

the atomic phase at the critical depth. No reasons are given why the atomic phase of hydrogen should have lesser viscosity than the molecular one.

To sum up, the ideas of Kuhn and Rittmann have brought into flux again a subject already hardened into a set of tenets that, perhaps, had found general consent too placidly. The discussion on the geophysical consequences of the new theory is by no means closed. In the meantime, it is natural to inquire how these ideas would affect our notions about the constitution of the other planets. Kuhn and Rittmann have remarked that the mean density of a planet ought to be greater the larger its mass is; because the solar matter would be in a state of higher compression. They are well aware of the low mean densities of the giant planets, but suspect that either vast cloud-filled atmospheres make these values spurious; or that the giant planets are distended structures of very high internal temperatures, which probably means they hold them to be gaseous throughout. Now, both of these explanations has already been disposed of in Section II of this review, so that we face a serious difficulty. On the theory of Kuhn and Rittmann the huge dimensions of the giant planets would rule out *a fortiori* gravitational separation leading to the formation of a heavy core. But the giant planets are known to have envelopes, far less dense than water, that comprise more than 80 per cent of their apparent volumes (*cf.* Table II). There appear to be only two ways of escaping this contradiction: either practically all the hydrogen and helium of the original solar matter which made up the primitive planets has boiled off, forming the envelopes of low density and leaving a residual core consisting of an undifferentiated mixture of the heavy elements; or the now existing envelopes are the products of later accretion from a gaseous substrate in which the primitive planets remained imbedded for a sufficiently long time. If the reviewer has understood correctly their concluding remarks on the stability of the planets, Kuhn and Rittmann would favour the first alternative. Though the authors do not say so explicitly, their argument from high viscosity against material differentiation would apply just as well to the rising of gas bubbles as to the sinking of crystals and droplets through a melt.

IV. *Cosmogonical Aspects*

For good reasons, all inquiries into the cosmogony of the solar system have dealt primarily with its geometric and mechanical features. Obvious regularities of that kind are numerous and thus have attracted attention for a long time. Furthermore, the science of mechanics, at least that of point masses and incompressible continua, had developed so rapidly that the theoretical apparatus for an attack on the mechanical problems of cosmogony was early available. On the contrary, our fragmentary knowledge of the chemical composition and physical composition of the planets and of the Sun is mostly of rather recent origin. As yet there is no sign of our having accomplished even an exhaustive inventory of the physico-chemical principles relevant to planetary constitution and cosmogony. The concluding remarks of this review are offered, therefore, with some reserve. Ultimately, it may be hoped, a complete cosmogonic theory will shed light on such puzzling details as the differences between the atmospheric composition and surface structure of the several terrestrial planets, or the varying strength of the methane bands in the giant planets. Confining ourselves to the grosser features of planetary structure, we may single out four different groups of phenomena which seem to deserve attention as possible clues to the history of the solar system:

A. The correlation between the mass of a planet and the size and composition of its atmosphere (oxides on the terrestrial planets and hydrides on the giant planets).

As was pointed out already in Section I, this correlation is well understood in general terms and indicates a great surplus of hydrogen on the giant planets.

B. The existence, in Saturn's system, of two types of satellites with densities greater than that of rocks and smaller than that of water, respectively, and the atmosphere of Titan. Kuiper's remarks on the cosmogonic significance of Titan's atmosphere have already been referred to.

C. The nature and origin of the envelopes of low density characteristic of all the giant planets. If Kuhn and Rittmann's views on the impossibility of gravitational separation should come to be generally accepted, the marked concentration of density toward the centre of the giant planets would constitute a forceful argument in favour of the accretion theory.

D. The mean chemical composition of the planets in relation to the composition of the Sun. The well-known scarcity of light elements on the terrestrial planets can always be explained by dissipation and, therefore, does not permit further cosmogonic inferences. The last column of Table III lists estimates of the mass ratio of the light elements (*H*, *He*, volatile compounds of low molecular weight) to heavy elements (metals and silicon, perhaps partly oxidized) in the several giant planets. These values were computed from the equation $M_1/M_2=\rho_1(1-\lambda^3)/\rho_2\lambda^3$ and range from 0·6 to 1·0. Rough as they may be, they set a limit to the composition of the planetary matrix. According to M. Schwarzschild's results, the same ratio for the solar interior is about 0·5. Considering the uncertainty of either estimate, there is no alarming discrepancy. If the planetary matrix were much richer in light elements than the bulk of the Sun, doubt would be thrown on the formation of the planets by sudden ejection from the Sun, which would have been accompanied by an unavoidable loss of hydrogen. When more accurate values for the mean composition of the Sun and the giant planets become available, they may facilitate a choice between the rival theories of the origin of the solar system, either through a sudden catastrophe followed by rapid condensation, or through gradual emergence by accretion.

RUPERT WILDT.

SOLAR ACTIVITY

Sunspots.—1946 was an outstanding year for sunspots and allied phenomena. It produced the largest and the second largest sunspot groups ever recorded at Greenwich: two of the most brilliant and extensive solar flares, and the highest prominence yet observed. The mean daily "sunspot number" was nearly treble that of the preceding year and ten times that of the last minimum year, 1944. Geophysical phenomena responded by a sudden increase in the number of radio fade-outs (ultra-violet radiation effects) and an increased frequency of "Sudden Commencements" (solar corpuscular effects), some of which heralded geomagnetic storms. Bursts of solar radiation observed on radio wave-lengths of about 5 metres made their appearance in early February, for the first time since "solar noise" was first detected four years ago. Yet, active though this year has been, the maximum of the present cycle may not occur for another year, if not for two.

Some 30 groups of sunspots, reached or exceeded 500 millionths of the Sun's visible hemisphere; 10 of these groups exceeded 1000 millionths. The group of record area, with central meridian passage on February 5–6, in N. latitude 27°, rose to 4900 millionths and had an average area during its disk passage of 4400 millionths. The second great spot with central meridian passage on July 26–27 in N. latitude 22° had a maximum area of 4000 millionths (*Observatory*, **66**, 267 and 347, 1946; *J.B.A.A.*, **56**, 65, 69 and 81, 1946). A third group with central meridian passage on December 17 approached 3000 area units.

The two intense solar flares of February 6 and July 25 respectively were each spectacular phases of activity of the two giant spots. The great extent of these flares will be appreciated from $H\alpha$ spectroheliograms taken at Mount Wilson and shown in *P.A.S.P.*, **58**, 86 and 317, 1946. A "great" magnetic storm followed each of the flares at respective time-intervals of 18 and $26\frac{1}{2}$ hours after peak brilliance. A remarkable broadening of the $H\alpha$ line in emission was observed at the peak intensity of the flare on July 25 (Ellison, *Observatory*, **66**, 358, 1946). Synchronously, there was a sudden burst of "solar noise". Similar bursts in association with flares occurring with the giant February spot are discussed by Appleton and Hey, *Phil. Mag.*, **37**, 73, 1946.

A prominence at the E. limb on June 4, not, however, connected directly with a sunspot, since its origin appeared to be in latitude 55° S., reached the phenomenal height of $1{\cdot}21 \times 10^6$ km. observed and $1{\cdot}70 \times 10^6$ km. as the deduced true height (*P.A.S.P.*, **58**, 310, 1946). Emanating from the disturbed region of the February sunspot were a persistent series of prominences observable in $H\alpha$ as broad absorption markings as the Sun's rotation carried them across the disk during several rotations (*J.B.A.A.*, **57**, 1947).

Geomagnetic activity was highest around five chief epochs: (1) Central meridian passage on February 5 and the solar flare on February 6 of the giant sunspot; (2) Just after the spring equinox, including central meridian passage on March 27 of a biggish sunspot; (3) April 23-24, i.e. about one solar synodic rotation after (2); (4) The solar flare on July 25 and central meridian passage on July 26 of the second giant spot; (5) An extended period around the autumnal equinox, including central meridian passage on September 19 of a large sunspot. These epochs include, collectively, six "great" storms of which that on March 28 was the most violent for five years (*Nature*, **157**, 187 and 435; **158**, 160 and 477, 1946).

H. W. NEWTON.

Prominences.—The mean daily areas and numbers of calcium prominences as derived from photographs taken at Kodaikanal on 258 days during the year are as follows:—

	Areas			*Numbers*		
	North	South	Total	North	South	Total
January to June	2·64	1·94	4·58 sq. mins.	5·17	4·70	9·87
July to December	1·61	1·54	3·15 ,,	4·79	3·89	8·68

Compared with figures of the previous year, the areas show an increase in the first half of the year and decrease in the second half; the numbers show a slight decrease. Both areas and numbers show a general preponderance over the northern hemisphere. The distribution of areas in latitude shows a maximum between 55° and 60° in the northern hemisphere and between 50° and 55° in the southern hemisphere. The numbers are maximum between 55° and 55° of latitude in both the hemispheres.

35 metallic prominences were observed with the prominence spectroscope, 24 in the northern and 11 in the southern hemisphere. Four of these appeared in the latitude zone 50° to 55° and the rest in lower latitudes.

Doppler displacements of the $H\alpha$ line in prominences were observed on 171 occasions, 56 towards the red, 59 towards the violet and 56 in both ways. The largest displacement of 8 A. towards the red was shown by a prominence on the South-east limb of the Sun at latitude 52° on 1946 September 29.

Observations with the spectrohelioscope showed Doppler displacements in prominences in 80 cases, 26 being towards red, 14 towards violet and 40 both ways. An eruptive arch-type prominence of height 6′ was photographed on the North-west limb of the Sun at latitude 42° on 1946 December 20.

The mean daily area of hydrogen absorption markings (without foreshortening correction) was 4907 millionths of the Sun's visible hemisphere—i. e. more than double the value for the previous year. The latitudinal distribution showed maxima between 35° and 40° N. and 20° and 30° S.

A. K. DAS.

COMETS

Three comets under observation at the end of 1945 were recorded also at the beginning of 1946, by G. van Biesbroeck at the Yerkes Observatory, before they were lost in twilight: the periodic comet Kopff 1945 b at magnitude 15 and the comet Väisälä 1944 b at magnitude 16·5, both on January 2, and that periodic comet of special interest, Schwassmann-Wachmann (1) = 1925 II, which was also under observation by H. M. Jeffers at the Lick Observatory.

This last-named comet, which has been photographed nearly every year since its discovery in 1927, and is noted for its extraordinary physical behaviour, experienced one of its most remarkable outbursts. It was 18^m in 1945 December and 16^m on January 1 when it showed a broad tail but hardly any coma. It then brightened rapidly from 13^m on January 11th to $9^m{\cdot}4$ on the 26th, during which time it developed a coma of 30″ and the nucleus lost its stellar appearance and appeared as a disk which expanded by the end of the month to about 20″. On January 26, while it was at its brightest, George H. Herbig successfully obtained plates with the nebular spectrograph of the Crossley telescope at Lick. These showed a solar type spectrum with no evidence of conspicuous bright lines. The comet then faded rapidly and by February 8 had dropped to 15^m, a fuzzy coma 45″ in diameter. On March 1, when last observed by Jeffers, it was a faint

coma 40″ diameter and of 18^m. It came under observation again in October, before opposition in December, and appeared nearly stellar, 19^m brightening to $15\frac{1}{2}^m$ in November.

The interesting nature of this object, and the possible connection of these outbursts with variations in solar activity, make it important to keep it under continuous observation. Van Biesbroeck and others have appealed for this to be done.

During 1946 four new comets were discovered and there was a further one announced, Johnson's Object, whose cometary nature has been in doubt. In addition three periodic comets were observed on their return to perihelion, and two others not at perihelion, Schwassmann-Wachmann (1) already mentioned, and Oterma 1943 a.

1946 a was discovered by Matthew Timmers, a Dutch Jesuit lay brother working at the Vatican Observatory at Castel Gandolfo, on the edge of a plate he had exposed on February 1 on the Selected Area No. 29 in Ursa Major. It was an object of the ninth magnitude with a well-marked central condensation in a coma about $2\frac{1}{2}'$ in diameter. A short tail was faintly recorded on photographs but could only be traced visually in a large telescope before moonlight interfered. Subsequently a fainter narrower second tail was photographed by Van Biesbroeck with the 24-inch reflector at Yerkes and found to be nearly in the normal direction, that is away from the Sun, the first and brighter tail being at 42° to it. Pre-discovery images, the earliest on January 23, were found by Whipple on Harvard patrol plates. The comet was well observed during the spring and summer when it was circumpolar. It reached $7^m.8$ on March 3 but started to fade slowly even before perihelion passage in April, on account of its increasing distance from the Earth. In August it appeared as tenth magnitude with a nearly stellar nucleus, round coma and no tail. By October 27 it was reduced to 15^m or 16^m, with little coma. A long series of photographs of it, 130 in all, covering practically the whole period of visibility in 1946, was obtained with the Zeiss astrographic telescope at the Vatican Observatory. The last observation in 1946, so far published, is for October 28 by L. Boyer at Algiers.

1946 b was the periodic comet Tempel (2), detected by Van Biesbroeck with the 24-inch reflector at Yerkes on May 1, magnitude 17, close to the position predicted by P. Ramensky. It brightened rapidly and by the time it reached perihelion, early in July, it was between 9^m and 10^m. Jeffers observing it at Lick found the coma fan-shaped, several minutes of arc across and with a sharp nucleus. On August 30 he estimated it as 8^m, easily visible in the 4-inch finder, a round coma 3′ in diameter and strongly condensed. Thereafter it slowly faded and was about 10^m to 11^m in mid-October. The last known observation was by H. L. Giclas at the Lowell Observatory on November 28.

1946 c was the periodic comet Giacobini-Zinner, detected by Jeffers at Lick on May 29, magnitude $16\frac{1}{2}$ and diameter 20″, very close to the position predicted by F. R. Cripps. By mid-August, when it was circumpolar, it had brightened to tenth magnitude, a small round coma with a trace of tail. It was at its brightest, 6^m, after perihelion in mid-September, declining to 11^m in November. A short broad tail was still visible at the end of October. Observations have been continued into the new year.

The return of this comet was chiefly remarkable for the meteor shower it occasioned on October 10, and this shower in turn was notable for being the first big shower to be well recorded by means of radar. As a spectacle the shower was not as brilliant as had been expected, even allowing for moonlight, and although the Earth was much closer to the comet and to its orbit than in 1933 the rate of naked eye meteors was only a

fraction of the rate on that occasion, and of unexpectedly short duration. The maximum, at the rate of 3000 to 4000 naked eye meteors an hour, was very sharply marked and lasted only a few minutes around 03.45 hours U.T. October 10.

1946 d was a new comet discovered on May 30 with a binocular comet seeker by Miss Ludmilla Pajdušáková at the Czechoslovakian Mountain State Observatory, Skalnaté Pleso, the reward of many hours of systematic sweeping. It was also found by David Rotbart, an amateur near Washington, D.C., while he was looking at some star clusters with a pair of 80 mm. binoculars; and by Weber in Germany. At discovery it was in Cygnus, an object of about seventh magnitude with a central condensation around a stellar nucleus of 10^m, and a tail about a degree long. It passed within 15 million miles of the Earth, retrograde motion carrying it across the sky at the rate of 14° a day. After brightening for a few days to 6^m, it faded rapidly, and when last photographed, by Jeffers at Lick on July 28, it was 17^m. Spectroscopic observations made at Sonneberg on June 3 showed a strong CN band $\lambda 3880$, and a continuous spectrum from $\lambda 3970$ to $\lambda 4960$; but the C band $\lambda 4700$ was not visible.

1946 e was the periodic comet Brooks (2), detected on June 28, $17^m{\cdot}5$, also by Jeffers at Lick, close to the position predicted by F. R. Cripps. It remained faint throughout and few observations of it appear to have been made other than by Jeffers. Even after perihelion in August, when it was expected to reach about 12^m, it seems to have been no brighter than 14^m. L. E. Cunningham has remarked that the observed magnitudes of the comet at previous apparitions have indicated some abnormality. However, though faint, it was still under observation at the end of the year.

1946 f was the designation given to the interesting periodic comet Oterma 1943 a (=1942 VII) observed again during the summer by Van Biesbroeck and Jeffers. It was discovered in 1943 at the Turku Observatory in Finland but, owing to the small eccentricity of its orbit (0·14) which lies between Mars and Jupiter, it can be followed throughout its path. The observations this year are notable in that they were made while the comet was at aphelion. It appeared as a small coma, nearly stellar and of 18^m, with a faint tail about 2′ long.

1946 g referred to an object of 12^m detected by Cecilio at La Plata on July 31 while searching for the periodic comet du Toit-Neujmin-Delporte (1941 e). It was mistaken for this comet but later thought to be a new comet. L. E. Cunningham however identified it as the minor planet 135 Hertha.

1946 h was a new comet, discovered on August 6 by Albert F. Jones, an amateur astronomer at Timaru, New Zealand, while locating the field of the variable star U Puppis. The coma appeared about 1′ in diameter, with a central condensation, the total magnitude being 9·0. It was observed till October 3, by which time it had brightened to seventh magnitude, increased in size and showed a short tail ; but it then became too near the Sun in the morning twilight for further observation before perihelion. It was recovered on 1947 January 3 by an exceptional observation, at very low altitude and within 23° of the Sun, made by H. L. Giclas at the Lowell Observatory. It was then 10^m.

1946 i was the object of 12^m discovered by E. L. Johnson at the Union Observatory, Johannesburg, on a photograph taken on August 21. His plates taken on September 3 and 15 showed " diffuse " images and, as the object could not be identified with any known planet, it was provisionally classified as a comet. The cometary nature has however not been confirmed, and eight plates taken with the Crossley reflector at Lick recorded the images as always stellar. It is considered therefore that the object is a

minor planet, and this conclusion is supported by the nature of its orbit with its small eccentricity (0·25) and short period (3·6 years).

1946 j refers to cometary images found by D. C. Berry at Dunedin, N.Z., on photographic plates exposed for comet Jones on September 3, 4 and 5. Although Berry himself doubted the evidence, the Carter Observatory considered it justified the announcement of a new comet. L. E. Cunningham however found the positions given could not be represented by an orbit and, from further examination of the plates, it seems the images were photographic faults which by coincidence lay nearly along a line.

1946 k was a new comet detected by Michiel Johan Bester at the Boyden Station of the Harvard College Observatory, at Bloemfontein, on a plate taken with the 3-inch Ross-Fecker patrol camera on October 31. It was in Caelum, an object of eleventh magnitude. It brightened to between 9^m and 8^m by December, by which time it had come sufficiently north in declination to be followed by observatories in northern latitudes. It was then seen as a coma about 2′ in diameter with a nucleus.

The periodic comets Wolf (2), Borrelly, and Schwassmann-Wachmann (3) of 1930, were due at perihelion during the year but were not seen. The first two were very badly placed for observation, but it was expected that the last-named would have been detected by southern observatories after perihelion in September when it was likely to have been between 13^m and 14^m.

Since 1937 a number of definitive elements of the orbits of comets have been published which have not been recorded in these Notes. Those that are now known to the writer have been tabulated below, together with some other reliable orbits; and the best available for recent comets are also included as usual. It seems desirable also to publish here a list of the annual numerical designations of comets (in order of perihelion passage) in order that they may be used, especially where the letter designations are uncertain. During the war, owing to the difficulties of communication, the announcements of new discoveries were sometimes greatly delayed or even lost. In consequence

Numerical Designations of Comets

Comet	*T*	Name	Year and letter
1939 I	Feb. 6·9	Kozik-Peltier	1939 a
II	Mar. 12·8	P/Kopff	1939 e
III	Apr. 10·2	Jurlof-Achmarof-Hassel	1939 d
IV	Apr. 26·1	P/Väisälä	1939 b
V	June 22·7	P/Pons-Winnecke	1939 c
VI	Aug. 9·5	P/Herschel-Rigollet	1939 h
VII	Sept. 15·4	P/Brooks (2)	1939 g
VIII	Oct. 3·5	P/Kulin	1940 a
IX	Nov. 5·6	Friend	1939 n
X	Nov. 10·8	P/Tuttle	1939 k
1940 I	Feb. 17·4	P/Giacobini-Zinner	1939 l
II	Apr. 23·5	P/Faye	1939 m
III	Aug. 15·8	Okabayasi-Honda	1940 e
IV	Oct. 7·9	Whipple-Paraskevopoulos	1940 d
1941 I	Jan. 16·2	Cunningham	1940 c
II	Jan. 20·4	Friend-Reese-Honda	1941 a
III	Jan. 22·5	P/Whipple	1940 b
IV	Jan. 27·7	de Kock-Paraskevopoulos	1941 c
V	Apr. 18·3	P/Encke	1941 b
VI	June 9·4	P/Schwassmann-Wachmann (1)	1941
VII	July 21·2	P/du Toit-Neujmin-Delporte	1941 e
VIII	Sept. 3·2	Van Gent	1941 d

Numerical Designations of Comets (Continued)

1942 I	Feb. 14·3	P/Schwassmann (2)	1941 f
II	Feb. 15·8	Väisälä	1942 c
III	Apr. 16·4	P/Forbes	1942
IV	Apr. 30·8	Whipple-Bernasconi-Kulin	1942 a
V	May 23·3	P/Grigg-Skjellerup	1942 d
VI	June 23·6	P/Wolf (1)	1942
VII	Aug. 21·8	P/Oterma=" Oterma (3) "	1943 a
VIII	Sept. 27·5	Oterma=" Oterma (1) "	1942 b
IX	Dec. 19·2	P/Stephan-Oterma=" Oterma (2) "	1942 f
1943 I	Feb. 6·7	Whipple-Fedke-Tevzadze	1942 g
II	Aug. 21·5	Daimaca	1943
III	Sept. 22·6	P/d'Arrest	1943
IV	Nov. 22·5	P/Daniel	1943
V	Nov. 26·0	P/Schaumasse	1944
1944 I	Jan. 12·5	Van Gent-Peltier-Daimaca	1943
II	Apr. 11·5	P/Comas Sola	1943
III	June 17·5	P/du Toit	1944 c
IV	July 17·7	Van Gent	1944

the letter designations were not always applied and confusion occurred in a few of the cases in which they were given. For completeness of reference the list given above has been extended to cover the years 1939 to 1944.* The symbol P/ has been introduced to denote a periodic comet, excluding however any with nearly parabolic orbits for which the dates of return are not predictable.

As a result of the difficulties of communication referred to, or for other reasons, the following comets were not noted in the previous annual reports :

1939 VIII P/Kulin 1940 a, discovered by G. Kulin at Budapest on 1940 January 6, an

Table of the Elements

Comet		*T* G.M.T. before 1925·0 U.T. from 1925·0	*q*	*e*
1889 I	Barnard-Brooks	1889 Jan. 31·1686	1·814918	1·001255
1908 III	Morehouse	1908 Dec. 25·7561	0·945300	1·000692
1910 III	Metcalf	1910 Sept. 16·2813	1·948009	0·999812
1916 II	P/Neujmin (2)	1916 Mar. 11·3161	1·339828	0·566494
1919 V	Metcalf-Borelly	1919 Dec. 7·3097	1·115272	1·000215
1925 II	P/Schw.-Wach. (1)	(1925 Mar. 2·734)	5·5466	0·13672
1927 I	P/Neujmin (2)	1927 Jan. 16·2273	1·338187	0·566819
1927 VI	P/Gale	1927 June 14·5681	1·213456	0·757425
1927 VIII	P/Schaumasse	1927 Oct. 1·3529	1·172087	0·705860
1929 I	P/Schw.-Wach. (2)	1929 Mar. 23·1300	2·090521	0·394547
1929 II	P/Forbes	1929 June 26·0463	1·528364	0·555822
1930 I	Schw.-Wach.-Peltier	1930 Jan. 15·6336	1·087102	0·999655
1930 II	Wilk	1930 Jan. 22·3098	0·672235	0·999028
1930 III	Wilk	1930 Mar. 28·8001	0·481816	0·992215
1930 VI	P/Schw.-Wach. (3)	1930 June 14·1955	1·011426	0·672477
1931 V	Carrasco	1931 Nov. 30·6696	2·330580	1·002217
1932 I	Houghton-Ensor	1932 Feb. 28·9294	1·254441	0·972148
		1932 Feb. 28·9288	1·254433	0·972130
1932 III	P/Kopff	1932 Aug. 21·4108	1·688183	0·518130
1932 VI	Geddes	1932 Sept. 21·0747	2·313566	1·001376
1935 II	P/Reinmuth	1935 Apr. 29·765	1·857376	0·503299
1936 I	Van Biesbroeck	1936 May 11·6340	4·04335	1·00197
1936 II	Peltier	1936 July 8·9551	1·099870	0·991760

* Up to and including 1940 they will be found in the Vierteljahrsschrift of the Astronomische Gesellschaft, and in the International Astronomical Union Circulars (*UAIC*). The present list is given in *UAIC*, No. 1098 (and No. 1104) but some perihelion dates have here been corrected.

object of 16^m at first taken to be a minor planet (1940 AB) but confirmed by three later observations, the only others, as cometary.

1941 III P/Whipple 1940 b, was detected on its return to perihelion by Leland E. Cunningham at the Oak Ridge Station of the Harvard College Observatory on 1940 September 1, about 15^m, within 6′ of the position predicted from the elements in the Planetary Coordinates, 1940–1960 volume, of the Nautical Almanac Office.

1942 II Väisälä 1942 c, discovered by Y. Väisälä at the Turku Observatory in Finland on 1942 March 11, 13^m, and as far as known under observation there for just over a month.

1945 g du Toit, referred to as 1945 f in the U.S.A.*, was discovered by du Toit at the Boyden Station of the Harvard College Observatory on 1945 February 11, 7^m. It appears to have been observed for only a few days. A preliminary orbit (ref. 56 in the following table) indicated the very small perihelion distance of 0·006 unit.

The comet du Toit 1945 c, which it was stated (*M.N.*, **106,** 77) was not seen again after discovery, was in fact under observation in South Africa for two months, and was there known as du Toit (4). It has been found by L. E. Cunningham (ref. 51 in the following table) to have an interesting orbit, the period, 4½ years, being the shortest known for a comet, excepting Encke.

In the main table which records the elements of the orbits, the predicted ones are marked with a "*p*" after the perihelion date, and are given only when the comet has been observed at that return. When so given, the perihelion date deduced from observation will be found either in another set of elements following the predicted, or in the notes appended under the reference number.

of Cometary Orbits

Period-years	ω	Ω	i	Equinox	Computer	Ref.	Comet
	°	°	°				
...	340·4597	357·4204	166·3689	1889·0	v. Biesbroeck	1	1889 I
...	171·5770	103·1614	140·1789	1908·0	v. Biesbroeck	2	1908 III
...	50·9703	289·5298	121·0504	1910·0	Viaro	3	1910 III
5·43	193·7833	327·6716	10·6290	1925·0	Neujmin	4	1916 II
...	185·7431	120·9743	46·3884	1919·0	Przybylski	5	1919 V
16·29	357·594	321·799	9·515	1932·0	Behrens	6	1925 II
5·43	194·7268	328·0024	10·6323	1950·0	Neujmin	7	1927 I
11·19	209·8458	67·0961	11·6216	1927·0	Cunningham	8	1927 VI
7·95	46·0045	90·6039	14·7194	1927·0	Kanda, Hirose	9	1927 VIII
6·42	357·7120	126·3273	3·7284	1950·0	Rasmusen	10	1929 I
6·38	259·4923	25·4905	4·6370	1929·0	Makarov	11	1929 II
...	325·0870	147·5566	99·9037	1930·0	Kulikov	12	1930 I
...	157·4951	178·9948	124·5194	1930·0	Koebcke	13	1930 II
...	46·9512	90·2624	67·1427	1930·0	Rechtenstamm	14	1930 III
5·43	192·3189	76·7797	17·4018	1930·0	Cripps	15	1930 VI
...	110·3080	17·8382	58·0662	1932·0	Carrasco	16	1931 V
302·3	303·5228	212·5321	74·2853	1932·0	Przybylski	17	1932 I
302·0	303·5222	212·5320	74·2847	1932·0	v. Schrutka	18	1932 I
6·56	19·7395	263·8353	8·7062	1925·0	Kepinski	19	1932 III
...	329·7014	215·1479	124·9959	1932·0	v. Biesbroeck	20	1932 VI
7·23	8·6885	124·9681	8·0667	1935·0	Kanda, Hirose	21	1935 II
...	44·9007	299·8609	66·1083	1950·0	v. Biesbroeck	22	1936 I
1542	148·4696	134·0482	78·5508	1936·0	Bobone	23	1936 II

* And 1945 f Friend-Peltier was called 1945 e in the U.S.A.

Table of the Elements

Comet		T	q	e
1938 I	P/Gale	1938 June 18·4700	1·182918	0·760735
		1938 June 18·4733	1·182888	0·760730
1939 I	Kozik-Peltier	1939 Feb. 6·8538	0·716503	0·994871
1939 III	Jurlof-Achm.-H.	1939 Apr. 10·1686	0·528271	0·998620
1939 V	P/Pons-Winnecke	1939 June 22·7230	1·101472	0·669486
1939 VI	P/Herschel-Rigollet	1939 Aug. 9·4640	0·748492	0·974176
1939 VII	P/Brooks (2)	1939 Sept. 15·4169	1·871443	0·486062
1939 VIII	P/Kulin	1939 Oct. 3·5212	1·749439	0·447694
1939 IX	Friend	1939 Nov. 5·647	0·94546	1·0
1941 III	P/Whipple	1941 Jan. 22·69*p*	2·4848	0·34995
1941 IV	de Kock-Paras.	1941 Jan. 27·6535	0·790003	0·998854
1941 VI	P/Schw.-Wach. (1)	1941 June 9·4237	5·522843	0·135507
1941 VII	P/du Toit-Neujmin	1941 July 21·2077	1·304632	0·582224
1942 I	P/Schw.-Wach. (2)	1942 Feb. 13·761*p*	2·143815	0·385449
1942 II	Väisälä	1942 Feb. 15·8162	1·24442	0·93369
1942 IV	Whipple-B.-K.	1942 Apr. 30·8333	1·445303	1·000893
1942 VI	P/Wolf (1)	1942 June 23·606*p*	2·437330	0·404797
1942 VII	P/Oterma	1942 Aug. 21·8085	3·389625	0·144425
1942 VIII	Oterma	1942 Sept. 27·516	4·112741	1·0
1942 IX	P/Stephan-Oterma	1942 Dec. 19·0991	1·594664	0·859947
		1942 Dec. 19·1967	1·595861	0·861140
1943 I	Whipple-Fedke-T.	1943 Feb. 6·7187	1·353628	0·992172
1943 II	Daimaca	1943 Aug. 21·546	0·75830	1·0
1943 III	P/d'Arrest	1943 Sept. 23·774*p*	1·385798	0·610627
1943 IV	P/Daniel	1943 Nov. 22·5086	1·526564	0·574328
1944 I	Van Gent-P.-D.	1944 Jan. 12·459	0·87218	1·0
1944 b	Väisälä	1945 Jan. 3·6557	2·400280	1·0
1945 c	P/du Toit	1945 Apr. 20·3046	1·234907	0·550617
1945 d	du Toit	1945 May 17·1456	0·998063	1·0
1945 a	P/Pons-Winnecke	1945 July 10·031*p*	1·159535	0·654672
		1945 July 10·5837	1·159164	0·654566
1945 b	P/Kopff	1945 Aug. 11·293*p*	1·495712	0·556068
1945 g	du Toit	1945 Dec. 28·012	0·006305	1·0
1946 a	Timmers	1946 Apr. 13·2531	1·724230	1·001312
		1946 Apr. 13·2698	1·724196	1·001341
1946 d	Pajdusakova-R.-W.	1946 May 11·4359	1·018251	1·0
1946 b	P/Tempel (2)	1946 July 2·268*p*	1·393240	0·542254
		1946 July 2·3440	1·393252	...
1946 e	P/Brooks (2)	1946 Aug. 25·940*p*	1·878739	0·484637
		1946 Aug. 25·970*p*	1·879484	0·484440
		1946 Aug. 25·7706	1·879383	...
1946 c	P/Giacobini-Z.	1946 Sept. 18·634*p*	0·995692	0·716683
		1946 Sept. 18·4871	0·995653	0·716683
1946 h	Jones	1946 Oct. 26·7938	1·136037	1·0
1946 k	Bester	1947 Feb. 7·4665	2·407127	1·0
		1947 Feb. 7·3988	2·407410	1·0
		1947 Feb. 7·4216	2·407373	1·0

References and Notes to Table of Elements

1889 I Barnard-Brooks. (1) G. van Biesbroeck, *Pub. Yerkes Obs.*, **8**, No. 4, 24, 1940. Definitive, from about 1100 observations covering 735^{d}. Osc. epoch 1889 February 5. Original orbit found to be elliptical: e=0·9999235 on 1870 January 1.

1908 III Morehouse. (2) G. van Biesbroeck, *Pub. Yerkes Obs.*, **8**, No. 5, 17, 1943. Definitive, from about 1300 observations covering 249^{d}. Osc. epoch 1908 December. 28 Original orbit found to be elliptical: e=0·999850 on 1888 June 11 (r=41).

of Cometary Orbits (continued)

Period-years	ω	Ω	i	Equinox	Computer	Ref.	Comet
	°	°	°				
10·99	209·1129	67·2556	11·7251	1950·0	Cunningham	24	1938 I
10·99	209·1162	67·2537	11·7254	1950·0	Cripps	25	1938 I
1650	169·0342	288·7561	63·5252	1939·0	Przybylski	26	1939 I
7500	89·2473	311·4283	138·1054	1939·0	Przybylski	27	1939 III
6·08	169·3590	96·7998	20·1178	1950·0	Porter	28	1939 V
156·0	29·2989	355·1295	64·1994	1939·0	Maxwell, Kaster	29	1939 VI
6·95	195·6839	177·7045	5·5461	1950·0	Dubiago	30	1939 VII
5·64	292·7546	137·6336	4·8020	1950·0	Kulin	31	1939 VIII
...	126·85	196·27	92·93	1939·0	Vergnano	32	1939 IX
7·47	190·468	188·814	10·223	1950·0	Sadler, McBain	33	1941 III
...	268·6693	42·2619	168·1947	1941·0	Chang, Li	34	1941 IV
16·15	356·2213	322·0041	9·5165	1950·0	Herget	35	1941 VI
5·52	69·2948	229·6448	3·2576	1950·0	Naur	36	1941 VII
6·52	358·0084	126·0433	3·7252	1950·0	Rasmusen	37	1942 I
85·5	335·2178	171·5925	38·0067	1950·0	Väisälä	38	1942 II
...	223·4177	340·1241	79·4447	1942·0	Iannini	39	1942 IV
8·29	160·9654	204·3426	27·3019	1950·0	Kamienski	40	1942 VI
7·89	354·8058	155·1708	3·9899	1950·0	Herget	41	1942 VII
...	163·6970	280·3839	172·5138	1942·0	Oterma	42	1942 VIII
38·42	358·2728	78·5068	17·8849	1942·0	Bobone	43	1942 IX
38·96	358·3611	78·4946	17·8908	1943·0	Dubiago	44	1942 IX
2274	39·8195	100·0230	19·7140	1943·0	Dubiago	45	1943 I
...	36·390	82·568	161·318	1943·0	Popovici	46	1943 II
6·71	174·4003	143·6293	18·0114	1950·0	Recht	47	1943 III
6·79	6·1035	70·4328	19·8461	1950·0	Dubiago	48	1943 IV
...	33·3983	57·9250	136·0544	1944·0	Möller	49	1944 I
...	239·1321	28·4314	17·2726	1950·0	Herget	·50	1944 b
4·56	203·3740	358·7246	6·4618	1945·0	Cunningham	51	1945 c
...	280·1413	254·2932	156·5093	1945·0	Bobone	52	1945 d
6·15	170·1065	94·4621	21·7136	1950·0	Ananieva	53	1945 a
6·15	170·1108	94·4553	21·6909	1950·0	Porter	54	1945 a
6·18	31·5410	253·0539	7·2246	1945·0	(Kepinski)	55	1945 b
...	50·93	321·62	137·02	1945·0	Cunningham	56	1945 g
...	54·3162	128·9125	72·8497	1946·0	Schmitt	57	1946 a
...	54·3268	128·9113	72·8484	1946·0	Cunningham	58	1946 a
...	22·2671	301·2565	169·5581	1946·0	Cunningham	59	1946 d
5·31	190·8586	119·4142	12·4306	1950·0	Ramensky	60	1946 b
5·31	...	...	...	...	Cunningham	61	1946 b
6·96	195·6049	177·6990	5·5398	1950·0	Dubiago	62	1946 e
6·96	195·5840	177·7058	5·5395	1950·0	Cripps	63	1946 e
6·96	...	...	...	...	Cunningham	64	1946 e
6·59	171·8518	196·2586	30·7402	1950·0	Cripps	65	1946 c
6·59	171·8200	196·2319	30·7264	1946·0	Cunningham	66	1946 c
...	320·4322	237·6283	56·9686	1950·0	Cunningham	67	1946 h
...	348·6609	34·8242	108·1619	1947·0	Bobone	68	1946 k
...	348·6335	34·8204	108·1661	1947·0	Schmitt	69	1946 k
...	348·6415	34·8615	108·1684	1950·0	Cunningham	70	1946 k

1910 III Metcalf. (3) Maria Viaro, *Capodimonte Contrib.*, **2**, No. 12, 1936. Definitive, from 656 observations covering 278^{d}. The comet is here called 1910 IV, following *V.J.S.*, **48**, 254; but this requires correction as perihelion preceded by 0^{d}·117 that of P/d'Arrest (*cf.* Recht, *A.J.*, **48**, 75) which becomes 1910 IV, as given in Crommelin's catalogue *Mem. B.A.A.*, **26** (2), 16, and in Yamarnato's Preliminary General Catalogue of Comets, *Pub. Kwasan Obs.*, **1**, No. 4, 22, 1936.

1916 II P/Neujmin (2). (4) G. N. Neujmin, *Poulkovo Obs. Circ.*, **32**, 53, 1941. Definitive, after combining 1916–1927. Osc. epoch 1916 April 10.

1919 V Metcalf-Borelly. (5) A. Przybylski, *Acta Astron.* (a), **4,** 59, 1939. Definitive, from 274 observations covering 180^{d}. Osc. epoch 1919 September 18·5. He intends to investigate the original orbit.

1925 II P/Schwassmann-Wachmann (1). (6) J. G. Behrens, *A.N.*, **245,** 309, 1932. Orbit based on preliminary investigation 1902–1931. Osc. epoch 1932 January 1. See also *A.N.*, **266,** 45.

1927 I P/Neujmin (2). (7) G. N. Neujmin, *Poulkovo Obs. Circ.*, **32,** 54, 1941. Preliminary orbit using 20 observations covering 97^{d} for best fit to the definitive orbit of 1916 II with perturbations to 1927. Osc. epoch 1927 March 4. Residuals of the order of $\pm 10''$ remained.

1927 VI P/Gale. (8) L. E. Cunningham, *HAC*, No. 444.* Definitive determination before linking to 1938. He plans to compute definitive elements combining 1927 and 1938. Osc. epoch 1927 July 19.

1927 VIII P/Schaumasse. (9) S. Kanda and H. Hirose, *UAIC*, No. 579.* From 5 observations combining 1919–1928. Osc. epoch 1927 November 1.

1929 I P/Schwassmann-Wachmann (2). (10) Hans Q. Rasmusen, *Pub. Copenhagen Obs.*, No. 106, 1935. From 4 normal places covering 1929–1935. Osc. epoch 1929 February 18. Another investigation, by N. M. Voronov, is noted in *Poulkovo Obs. Circ.*, **16,** 21, 1936.

1929 II P/Forbes. (11) Mrs N. Makarov, *A.J.*, **50,** 37, 1942. Definitive, from 72 observations covering 94^{d}. Osc. epoch 1929 September 6. Prediction for 1942 is given.

1930 I Schwassmann-Wachmann-Peltier. (12) D. K. Kulikov, *Pub. Obs. Astron. Univ. Leningrad*, **12,** 231, 1941. Definitive, from 30 observations covering 28^{d}. *Cf.* F. Koebcke quoted in *M.N.*, **97,** 334, 1937.

1930 II Wilk. (13) F. Koebcke, *Poznan Obs. Reprint*, No. 10, 35, 1946. Definitive, from 212 observations covering 38^{d}.

1930 III Wilk. (14) G. von Schrutka-Rechtenstamm, *UAIC*, No. 1081. Definitive, from 244 observations covering 103^{d}. Osc. epoch 1930 April 2.

1930 VI P/Schwassmann-Wachmann (3). (15) F. R. Cripps, MS. From 142 observations. Perturbations and corrections to Sun's tabular places applied.

1931 V Carrasco. (16) R. Carrasco, *Bol. Astron. Obs. Madrid*, **3,** No. 5, 1946. Definitive, from 65 observations covering 85^{d}.

1932 I Houghton-Ensor. (17) A. Przybylski, *UAIC*, No. 1081; and to appear in *Acta Astron.* Definitive, from 113 observations covering 64^{d}. (18) Mrs. Erna von Schrutka, *UAIC*, No. 1081. Definitive, from 121 observations covering 64^{d}. Osc. epoch 1932 April 1.

1932 III P/Kopff. (19) F. Kepinski, *Pub. Inst. Astron. pratique* (Varsovie), No. 20, 1938, and *Bul. Ac. Pol. Sci.* (A), **1938,** 180. Definitive, from observations of 1932 (5 normal places) linked to 1926. Osc. epoch 1932 October 13·5.

1932 VI Geddes. (20) G. van Biesbroeck, *Pub. Yerkes Obs.*, **8,** No. 3, 13, 1937. Definitive, from 303 observations covering 1070^{d}. Osc. epoch 1932 October 23. Original orbit found to be elliptical: $e=0{\cdot}9994868$ on 1927 December 6.

1935 II P/Reinmuth. (21) S. Kanda and H. Hirose, MS., and (?) *Tokyo Astron. Obs. Report*, **4,** 20–24, 1936. From 5 observations combining 1928–1935. Osc. epoch 1935 January 30. *UAIC*, No. 574 gives 1936 elements presumably derived from these. The period indicated by these elements is 32 days shorter than that given in the prediction by Foxell and Levin in *B.A.A. Handbook*, 1935 (quoted in *M.N.*, **96,** 346). It appears that it is the latter which is in error, and hence, too, the 1942 prediction by H. Summer (*B.A.A. Handbook*, 1942) which was based on it.

1936 I Van Biesbroeck. (22) G. van Biesbroeck, *Pub. Yerkes Obs.*, **8,** No. 4, 7, 1940. Definitive, from 125 observations covering 830^{d}. Osc. epoch 1936 May 2. Original orbit found to be elliptical: $e=0{\cdot}99917$ on 1916 April 6 ($r=38$).

1936 II Peltier. (23) Jorge Bobone, *Res. Obs. Nac. Argentino*, **36,** No. 1, 52, 1938. Definitive, from 636 observations covering 159^{d}. Osc. epoch 1936 May 23.

1938 I P/Gale. (24) L. E. Cunningham, *HAC*, No. 452. From 12 observations covering 27^{d} with assumed period 10·99294 years linking the orbit to 1927. He intends to revise the orbit 1927–1938. (25) F. R. Cripps, MS. Provisional revision of orbit using 7 observations covering 55^{d}, and new computation linking it to 1927. Osc. epoch may be taken as 1938 July 1.

1939 I Kozik-Peltier, 1939 a. (26) A. Przybylski, *UAIC*, No. 752. From 89 observations covering 26^{d}. He has undertaken the definitive orbit.

1939 III Jurlof-Achmarof-Hassel, 1939 d. (27) A. Przybylski, *UAIC*, No. 781. From 26 observations covering 30^{d}. The definitive orbit has been undertaken by M. Bielicki.

* *HAC=Harvard College Observatory Announcement Card.*
UAIC=Union Astronomique Internationale Circulaire.

1939 V P/Pons-Winnecke, 1939 c. (28) J. G. Porter, *B.A.A.J.*, **54,** 137, 1944. Definitive, from 225 observations covering 7 months. Osc. epoch 1939 August 5. Orbit not linked to previous apparitions. Close approach to Earth: 0·10725 A.U. on July 1.

1939 VI P/Herschel-Rigollet, 1939 h. (29) A. D. Maxwell and Katherine P. Kaster, *A.J.*, **49,** 59, 1940. Definitive, from 89 observations covering 146^d; and a normal place 25 days later, from 4 subsequent observations, is represented to 2″. Osc. epoch 1939 August 5. Identity with Caroline Herschel's comet 1788 II is now considered certain.

1939 VII P/Brooks (2), 1939 g. (30) A. Dubiago, *Astron. Circ.* (*U.S.S.R.*), No. 47, 1946. Elements deduced after combining 1925, 1932–33 and 1939–40. He finds a secular acceleration to the mean motion $+3733'' \times 10^{-9}$ ($t - t_0$ days).

1939 VIII P/Kulin, 1940 a. (31) G. Kulin, *UAIC*, Nos. 810 and 904. From the only 4 observations available; they cover 24^d. *V.J.S.*, **77,** 76, 1942 gives account. (See also p. 108).

1939 IX Friend, 1939 n. (32) A. M. Vergnano, *UAIC*, No. 805. From observations covering 22^d.

1941 III P/Whipple, 1940 b. (33) D. H. Sadler and Miss F. M. McBain, *Pub. N.A. Office* "Planetary Coordinates 1940–1960", xvi., 1939. Predicted elements. Observations indicated T 1941 January 22·464, 0^d·23 earlier than predicted (L. E. Cunningham, *HAC*, No. 531).

1941 IV de Kock-Paraskevopoulos, 1941 c. (34) Y. C. Chang and C. C. Li, *A.J.*, **51,** 51, 1944. Improved orbit from 15 observations covering 5½ months, perturbations neglected. Residuals of the order of 15″ remain.

1941 VI P/Schwassmann-Wachmann (1) = 1925 II. (35) Paul Herget, *B.A.A. Handbook*, 1948. Definitive elements from observations 1934–1944. Osc. epoch 1941 January 6, $M = 350°·57422$.

1941 VII P/du Toit-Neujmin-Delporte, 1941 e. (36) Peter Naur, *Pub. Copenhagen Obs.*, No. 141, 1945. Definitive, from 54 observations covering 86^d. Osc. epoch 1941 August 29. Jupiter perturbations only included.

1942 I P/Schwassmann-Wachmann (2), 1941 f. (37) H. Q. Rasmusen, *Pub. Copenhagen Obs.*, No. 128, 1941. Prediction from his 1935 orbit previously noted (*M.N.*, **96** 346). Observations indicated T 1942 February 14·29.

1942 II Väisälä, 1942 c. (38) Y. Väisälä, *UAIC*, No. 910. From observed arc 32^d.

1942 IV Whipple-Bernasconi-Kulin, 1942 a. (39) G. M. Iannini, *Pub. La Plata Obs.*, **21,** No. 2, 19, 1945. Definitive, from 228 observations covering 376^d. Osc. epoch 1942 May 1. Original orbit found to be elliptical: $1/a = +0·0002613$ on 1937 September 24 ($r = 14$).

1942 VI P/Wolf (1). (40) M. Kamienski, *Warsaw Obs. Circ.*, No. 22, 1946. Improved prediction (cf. *A.J.*, **49,** 164, 1942) based on his previous very exact investigations of the orbit from 1884 onward. Osc. epoch 1942 June 10. Baade's observation 1942 November 5 (mag. 19·3) indicates T 1942 June 23·55. Kamienski has previously found a secular deceleration to the mean motion: $\Delta n = -0''·00000042$ ($t - t_0$). See also *M.N.*, **106,** 269 where M for 1942 June 10·0 should read 358° 22′ 54″·10.

1942 VII P/Oterma, 1943 a, which was called Oterma (3). (41) Paul Herget, *HAC*, No. 698, and *B.A.A. Handbook*, 1947. Definitive, from observations (7 normal places) covering 440^d, 1943–44. Osc. epoch 1943 October 3·0.

1942 VIII Oterma, 1942 b, which was called Oterma (1). (42) Miss L. Oterma, *UAIC*, No. 923. From observed arc 67^d.

1942 IX P/Stephan-Oterma, 1942 f, which was called Oterma (2), and Tevzadze (1) in U.S.S.R. It is identical with 1867 I Stephan. (43) Jorge Bobone, *HAC*, No. 646. From observed arc 28^d. (44) A. D. Dubiago, *Astron. Circ.* (*U.S.S.R.*), No. 17, 1943. From observed arc 36^d.

1943 I Whipple-Fedke-Tevzadze, 1942 g, which was called Tevzadze (2) in U.S.S.R. (45) A. D. Dubiago, *Astron. Circ.* (*U.S.S.R.*), No. 21, 1943. From 72 Soviet observations covering 171^d; perturbations were neglected.

1943 II Daimaca. (46) Calin Popovici, *UAIC*, No. 970. Elements from a 2^d arc, in close agreement with those by P. Naur from the same observations (cf. *M.N.*, **104,** 108, 1944).

1943 III P/d'Arrest. (47) A. W. Recht, *HAC*, No. 655. Prediction based on his 1923 elements which gave the best fit 1910–1923. Osc. epoch 1943 April 2. Observations indicate T 1943 September 22·6. His investigation covering eight apparitions 1851–1923 (*A.J.*, **48,** 65, 1939) showed secular increases in the semi-major axis and eccentricity: $\Delta a = +0·000151$ and $\Delta e = +0·0000169$ per revolution.

1943 IV P/Daniel. (48) A. Dubiago, *A.J.*, **52,** 88, 1946. From 7 observations covering 140^d. Perturbations neglected and period not linked to previous apparitions.

1944 I Van Gent-Peltier-Daimaca. (49) J. P. Möller, *UAIC*, No. 980. From 7 approximate observations covering 39^d. Residuals average about 1′. Elements are in accord with J. Jackson's preliminary orbit (*HAC*, No. 673).

1944 b Väisälä. (50) Paul Herget, *HAC*, No. 695. From 5 observations covering 116^d.

1945 c P/du Toit, was called du Toit (1), and du Toit (4) in South Africa. (51) L. E. Cunningham, MS. From observations covering 58^d. The period, which he considers is uncertain by only a few days, is the shortest known for a comet other than P/Encke.

1945 d du Toit, was called du Toit (2). (52) Jorge Bobone, *HAC*, No. 719. From observations covering 25^d.

1945 a P/Pons-Winnecke. (53) L. Ananieva, *Astron. Circ.* (*U.S.S.R.*), No. 41, 1945. Prediction based on the *B.A.A. Handbook* 1939 prediction by A. E. Levin and J. G. Porter, with perihelion date and period corrected. Osc. epoch 1945 July 4. (54) J. G. Porter, MS. Provisional orbit from the 1945 observations after linking to the 1939 apparition. Osc. epoch 1945 July 4.

1945 b P/Kopff. (55) Elements deduced by J. G. Masters (MS) from the accurate ephemeris of perturbed places by F. Kepinski, *Pub. Inst. Astron. pratique* (*Varsovie*), 23, 1946. Osc. epoch 1945 August 13. Observations indicated T 1945 August 11·275. Kepinski states that all his records of the computations of this comet from 1924–1944, except the ephemeris mentioned, were destroyed in the Warsaw insurrection of 1944 August. The comet made a close approach to Jupiter to 0·57 A.U., in the spring of 1943, which increased the mean motion by about 30″ (*cf.* ref. 19 above).

1945 g du Toit, was called du Toit (3) and designated 1945 f in the U.S.A. (56) L. E. Cunningham, *HAC*, No. 733. Elements from rough positions covering 4 days.

1946 a Timmers. (57) A. Schmitt, *UAIC*, No. 1043. From 3 observations covering 84^d. (58) L. E. Cunningham, *HAC*, No. 809. From 5 observations covering 261^d, with first order Jupiter perturbations included. Osc. epoch 1946 March 1.

1946 d Pajdusakova-Rotbart-Weber. (59) L. E. Cunningham and Miss E. L. Scott, *HAC*, No. 751. From observations covering 4^d, but owing to the comet's proximity to the Earth and consequent large apparent motion, the elements proved very accurate and an observation 8 weeks later, on July 28, is represented to about 4″. Cunningham is undertaking a definitive orbit.

1946 b P/Tempel (2). (60) P. Ramensky, *UAIC*, No. 1040. Predicted elements. (61) L. E. Cunningham, *HAC*, No. 747. He compared Ramensky's elements with observations and corrected the perihelion date and period (to 5·31016 years).

1946 e P/Brooks (2). (62) A. Dubiago, *Astron. Circ.* (*U.S.S.R.*), No. 47, 1946. Prediction from the 1939 elements resulting from his investigation of the orbit 1925–1940; see ref. (30) above. (63) F. R. Cripps, *B.A.A. Handbook*, 1946. Prediction based on the previous one (*Handbook*, 1939) with perihelion date corrected. (64) L. E. Cunningham, *HAC*, No. 761. He compared Cripps's elements with observations and corrected the perihelion date and period (to 6·95992 years).

1946 c P/Giacobini-Zinner. (65) F. R. Cripps, *B.A.A. Handbook*, 1946. Prediction based on the previous one (*Handbook*, 1939) with perihelion date corrected. Perturbations by the Earth in 1939 were included with those of Jupiter and Saturn. (66) L. E. Cunningham, *HAC*, No. 775. He modified Cripps's elements, correcting the perihelion date and period (to 6·58799 years), and altered a direction cosine arbitrarily to fit the observations.

1946 h Jones. (67) L. E. Cunningham, *HAC*, No. 792. From two observations in 1946 August and one 1947 January, covering an arc of 143^d.

1946 k Bester. (68) Jorge Bobone, *HAC*, No. 794. From 3 observations covering 66^d. (69), A. Schmitt, *UAIC*, No. 1079. From observations covering 77^d. (70) L. E. Cunningham, *HAC*. No. 811. From observations covering 130^d.

Corrigenda

The following corrections are to previous reports on comets in these Council Notes:

95, 386, Table. For " 1934 II ", for P/Enke, read " 1934 III ".

98, 348, Table. Under column heading for *T*, add " G.M.T. before 1925·0 ". In elements for 1929 I P/Schwassmann-Wachmann (2), for *T* 1929 " May 12·85339 " read " March 23·19990 ". In elements for 1935 I Johnson, for period " 1216·4 " read " 900·4 ".

99, 409, 2nd para., line 3. After " *Association* " add " Vol. 30 ".

100, 328, Table. In elements for 1939 m P/Faye, for perihelion distance *q* " 3·80291 " read " 1·65046 ".

102, 107, line 25. After " Comet de Kock ", for " 1941 a " read " 1941 c " and delete " (1941 c) " at end of line.

102, 108, Table. In elements for 1941 e du Toit-Neujmin, for period " 5·44560 " read " 5·44538 ". In elements for P/Schwassmann-Wachmann (2), for year of perihelion " 1941 " read " 1942 ".

106, 77, line 14 from bottom of page. For " not seen again " read " observed in South Africa for two months ".

G. MERTON.

DOUBLE STARS

New Pairs.—Luyten and Jose, six proper motion pairs with at least one degenerate component (*I.A.U. Circ.*, 1063).

Measures.—Ann. Dearborn Obs., Vol. 6 contains measures by the late Phillip Fox, prepared for publication by van Biesbroeck. Photographic measures are given by Alden (*A.J.*, **51,** 195), Strand (*A.J.*, **52,** 1) and Popovici (*Circ. Bucarest Astr. Obs.*, 1946 June 1).

Orbits:

Double Star	*P*	*e*	*a*	Computer	Reference
	y		″		
ADS 671	400·9	0·426	10·95	Baize	*A.J.*, **51,** 221
,, 755	166·46	0·325	0·986	Baize	*A.J.*, **51,** 221
,, 918	33·66	0·20	0·15	Eggen	*A.J.*, **51,** 232
,, 1613	26·5	0·0	0·20	Eggen	*A.J.*, **51,** 232
	13·25	0·90	0·24		
,, 2612	∞	1·0	(0·405)	Ekenberg	
,, 3064	7·2	0·22	0·14	Eggen	*A.J.*, **52,** 83
,, 3098	179·2	0·495	0·55	Ekenberg	
,, 4153	150	0·87	0·600	van den Bos	*A.J.*, **52,** 88
,, 5234	111·0	0·746	0·889	Ekenberg	
,, 6762	435	0·20	0·654	Ekenberg	
,, 6811	21·8	0·00	0·17	Eggen	*A.J.*, **52,** 83
,, 7334	15·0	0·10	0·166	Ekenberg	
,, 7662	43·0	0·61	0·25	Eggen	*A.J.*, **52,** 83
,, 7871	232·0	0·041	0·549	Ekenberg	
,, 8419	115	0·50	0·280	Ekenberg	
,, 8635	80·0	0·10	0·426	Ekenberg	
,, 9397	20·50	0·038	0·184	Ekenberg	
,, 9505	8·0	0·45	0·10	Eggen	*A.J.*, **52,** 83
,, 10585	69·5	0·28	0·60	Eggen	*A.J.*, **51,** 232
,, 10871	35·8	0·45	0·28	Eggen	*A.J.*, **51,** 232
,, 12961	90·0	0·0	0·218	Ekenberg	
,, 17052	28·2	0·29	0·24	Eggen	*A.J.*, **52,** 83
$8^h\ 24^m{\cdot}2\ -52°$	13·73	0·23	0·160	van den Bos	*A.J.*, **52,** 63
$9^h\ 26^m{\cdot}8\ -40°$	34·11	0·440	0·920	van den Bos	*A.J.*, **51,** 198
$18^h\ 14^m{\cdot}0\ -61°$	6·07	0·26	0·023	Alden	*A.J.*, **52,** 73
$22^h\ 44^m{\cdot}4\ -33°$	27·22	0·525	0·206	van den Bos	*A.J.*, **52,** 75

Ekenberg's orbits are contained in "A study of visual binary stars", *Medd. Lund astr. Obs., Ser. II, No.* 116.

Miscellaneous.—Kooreman (*B.A.N.*, **10,** 169) gives differences in photovisual magnitudes between the components of double stars; Luyten (*A.J.*, **52,** 35) has a note on binary stars with white dwarf components; van Biesbroeck (*A.J.*, **52,** 34) on visual observations of close double stars—performance of a large reflector; Burns (*A.J.*, **52,** 38) on double stars at Allegheny Observatory; Payne Gaposchkin (*A.J.*, **52,** 29) on the relation between components of binary stars; Russell (*A.J.*, **52,** 25) on the determination of the orbits of binary stars; and Aitken (*A.J.*, **52,** 32) on the outlook for double-star astronomy.

Harris (*A.J.*, **52,** 84) gives a graphical solution of orbits of visual binaries; Russell (*P.A.*, **54,** 162) writes on the determination of the elements of binary stars; Barbier

(*Bull. astr. Paris*, **12,** 411) on the distribution of the poles of the orbits of double stars; Wallenquist (*Ann. astr. Obs. Uppsala*, Vol. 1, No. 5) on the apparent distribution and properties of triple and multiple stars; Treanor (*Observatory*, **66,** 255) on the telescopic resolution of unequal binaries; de Vaucouleurs (*Publ. Obs. Houga*, Nos. 4, 5, 6) on a method of determining the distances of double stars below the separating power.

Baize and Romani (*Ann. Astrophys.*, **9**) give new formulae for computing dynamical parallaxes; Brouwer (*A.J.*, **52,** 57) gives a survey of the dynamics of close binary systems.

W. H. VAN DEN BOS.

ADDRESS

*Delivered * by the President, Professor H. H. Plaskett, on Astronomical Spectroscopy*

Introduction.—The stars are unrivalled sources of gently excited spectra, and through these spectra provide indispensable clues to our knowledge of atomic structure. Thus Huggins's discovery of the ultra-violet lines of hydrogen first made clear an obvious regularity in the wave-lengths of these lines, and led in turn to Balmer's law and Rydberg's identification of spectroscopic terms. Lockyer's recognition that a single atom could give normal and enhanced spectra, and A. Fowler's discovery that λ4686 and the Pickering series, first found in O-type stars, were enhanced spectra of helium, each played a vital part in Bohr's application of the quantum theory to the nucleus atom and his demonstration that enhanced spectra, with series characterized by Rydberg constants $4R$, $9R$ etc. were due to ionized atoms which had lost one, two or more electrons. Again Saha's theory of thermal ionization and his description of the Harvard spectral classes as a temperature sequence, together with the work of R. H. Fowler and Milne on the significance of line maxima in this sequence, greatly stimulated the analysis into spectroscopic terms of the complex spectra and led to A. Fowler's and Russell's powerful contributions to this field. Lines of unknown origin, found in the spectra of the gaseous nebulae, the solar corona and various stars, led to Bowen's discovery that normally forbidden transitions between stationary states were occurring in the atoms in these sources ; the step-by-step identification of these lines by Bowen, Edlén, Merrill and others resulted in an intensive study of extreme ultra-violet spectra, notably by Edlén himself, and led to the discovery of further regularities among the stationary states in stripped atoms. The fact that in the solar spectrum alone there are between λ2914 and λ13945 some 8112 lines without identification † clearly indicates that the stars may still have some contributions to make to our knowledge of atomic structure. These investigations, in which astronomers have taken an honourable part, and which culminated in the development of quantum-mechanics, have had widespread consequences for physics and astronomy. With the solution, however, of its major problems, this phase of spectroscopy must be regarded as nearly ended, and the interest of physicists, at least, has tended to turn elsewhere.

To the physicist spectroscopy is only one weapon in a rich armoury. To the astronomer, on the other hand, spectroscopy provides almost the only means of learning about the physics of stellar atmospheres, and it is therefore not surprising that largely in his hands spectroscopy is passing into a second phase to be described as *astronomical spectroscopy*. By astronomical spectroscopy I shall mean those methods, involving an accurate knowledge of the atomic line-absorption coefficient and of the transfer of radiation in a gaseous medium, which permit a determination of the numbers of atoms in various stages of excitation and ionization in the stellar atmosphere. It is thus a quantitative technique for investigation in astrophysics just as X-ray analysis and electron diffraction are quantitative techniques for the investigation of the physics of crystals.

* The Address was a descriptive account of the topics here dealt with at greater length and in a slightly more systematic form.

† Private communication from Dr Charlotte Moore-Sitterly.

Astronomical spectroscopy may be said to have begun with the work of Schwarzschild on radiative transfer in continuous and line spectra, and in its early days significant contributions to it were made by Schuster, by Milne and by J. Q. Stewart. To A. Unsöld belongs, however, the honour of presenting in 1927 * the first papers on astronomical spectroscopy proper, while his *Physik der Sternatmosphären* with its complete list of references and its elegant presentation of theory and observation is the standard text-book of the subject. In these papers Unsöld was able to show from his own observations of the profiles of the *Na* D-lines across the disk of the Sun that the lines were formed closely in accordance with the equation of transfer set up by Schuster and Schwarzschild, and from the classical theory of dispersion he succeeded in finding the number of *Na* atoms in the ground state per square cm. column of the solar atmosphere. Following these papers development was rapid, and I need only remind you of Eddington's† clarification of the mode of formation of solar and stellar absorption lines, our Medallist's ‡ establishment of the curve of growth in the Sun, and Struve and Elvey's § discovery of " turbulence " in stellar atmospheres to show how soon astronomical spectroscopy established itself as a new mode of investigation.

Twenty years have elapsed since the publication of Unsöld's papers, and it is not inappropriate to attempt now to assess some of the results of this new mode of attack. I propose therefore this evening to take full advantage of the freedom given by Council to a President in his Annual Address and to discuss some of the work which has been done on astronomical spectroscopy. Since the whole subject is intimately bound up with the atomic line-absorption coefficient and the equation of transfer, I shall devote the first two parts of the address to these topics. In the third part I shall discuss some of the work which has been done on the curve of growth, and shall conclude by indicating some directions where, in my opinion, further investigation is needed.

1. *The Atomic Line-Absorption Coefficient*

1.1. *The Classical Oscillator.*—The classical oscillator is a fictitious mechanism of peculiar importance since alone among mechanisms obeying the simple laws of classical mechanics and electrodynamics it absorbs and emits a discrete frequency or line. It may therefore be anticipated that it will mimic in its behaviour some of the properties of the actual atoms obeying the laws of quantum-mechanics. The oscillator consists of an electron of charge ϵ and mass m, elastically attracted to a centre of force through which it oscillates in simple harmonic motion with a constant frequency ν_0. In the course of its motion the electron is accelerated, and in accordance with electrodynamics radiates energy of this frequency. The electron is therefore damped and its equation of motion is given by

$$\ddot{x}+(2\pi\nu_0)^2x+\gamma_0\dot{x}=0,$$

where

$$\gamma_0=\frac{8\pi^2\epsilon^2\nu_0^2}{3mc^3} \qquad (1)$$

is the classical damping constant. The amplitude of oscillation is

$$x(t)=x_0e^{-\gamma/2t}\ \cos(2\pi\nu_0t-\phi).$$

The oscillator will therefore emit a wave-train of constant frequency ν_0, and this wave-

* A. Unsöld, *Z. Phys.*, **44**, 793, 1927; **46**, 765, 1928.
† A. S. Eddington, *M.N.*, **89**, 620, 1929.
‡ M. Minnaert and G. F. W. Mulders, *Z. Astrophys.*, **1**, 192, 1930 ; **2**, 165, 1931.
§ O. Struve and C. T. Elvey, *Ap. J.*, **79**, 409, 1934.

train, observed at any point in its path, will show with the passage of time an exponential decrease of amplitude. It is only a homogeneous wave-train of infinite duration and constant amplitude which the spectroscope shows as a line of the frequency ν_0, while a non-homogeneous wave-train, such as that emitted by the classical oscillator, is analysed into the sum of an infinite number of homogeneous wave-trains of varying frequency and amplitude. Such an analysis is effected by Fourier's integral theorem, so that

$$x(t)=2x_0\int_0^\infty d\nu\int_0^\infty e^{-\frac{\gamma_0}{2}\tau}\cos 2\pi\nu_0\tau\times\cos 2\pi\nu(\tau-t)d\tau$$

$$=x_0\int_0^\infty\left[\frac{1}{4\pi^2(\nu-\nu_0)^2+\left(\frac{\gamma_0}{2}\right)^2}\right]^{\frac{1}{2}}\cos(2\pi\nu t-\psi)d\nu$$

neglecting terms with $(\nu+\nu_0)^2$ in the denominator. The intensity, $I_\nu d\nu$, proportional to the square of the amplitude, of the homogeneous wave-train with frequency between ν and $\nu+d\nu$ is therefore

$$I_\nu d\nu=\frac{K}{4\pi^2(\nu-\nu_0)^2+\left(\frac{\gamma_0}{2}\right)^2}d\nu,$$

where K is a constant of proportionality. If $I_0=\int_0^\infty I_\nu\,d\nu$ is the total intensity of the emitted line, we find

$$I_\nu d\nu=I_0\frac{\gamma_0}{4\pi^2(\nu-\nu_0)^2+\left(\frac{\gamma_0}{2}\right)^2}d\nu=I_0\frac{\delta_0}{\pi}\frac{1}{(\nu-\nu_0)^2+\delta_0^2}d\nu, \tag{2}$$

so that the damped wave emitted by the classical oscillator is analysed by the spectroscope into a broadened line whose half half-width (the distance from the centre of the line to the point where the intensity is one-half that at the centre) is given by

$$\delta_0=\frac{\gamma_0}{4\pi}=5{\cdot}08\times10^6\ \text{sec.}^{-1}=0{\cdot}000059\ \text{A.} \tag{3}$$

This half half-width, δ_0, is well below the limits of ordinary spectroscopic resolution, and it might therefore be thought that the widened line predicted by the classical oscillator was of no practical importance. However, beyond the limits $\pm\delta_0$ the intensity decreases only as $(\nu-\nu_0)^{-2}$, that is exceedingly slowly, so that the wings of the predicted emission line should be readily observable.

What is true of the emission of a classical oscillator is also true of its absorption. It may be shown * that on the passage of an electromagnetic wave through a medium of $\tilde{N}$ classical oscillators per unit volume there is exponential absorption and dispersion, the absorption-coefficient being given by

$$k_\nu d\nu=\frac{\pi\epsilon^2}{mc}\tilde{N}\frac{\gamma_0}{4\pi^2(\nu-\nu_0)^2+\left(\frac{\gamma_0}{2}\right)^2}d\nu=\frac{\pi\epsilon^2}{mc}\tilde{N}\frac{\delta_0}{\pi}\frac{1}{(\nu-\nu_0)^2+\delta_0^2}d\nu, \tag{4}$$

where γ_0 and δ_0 are defined as before. This absorption arises because the energy of the wave-train is used up in making the classical oscillators perform forced vibrations.

Broadening of the absorption or emission line given by a classical oscillator arises, however, not only from damping but also from collisions (Lorentz broadening). If the

* A. Unsöld, *Physik der Sternatmosphären*, p. 148, 1938.

effect of a collision is to quench the radiation emitted by a classical oscillator, then the amplitude of the emitted wave-train at any point in its path may be represented by

$$x(t)=x_0 e^{-\frac{\gamma_0}{2}t}\cos 2\pi\nu_0 t \quad \text{for} \quad 0\leqslant t<T$$

$$=0 \qquad\qquad\qquad\qquad \text{for} \quad t<0,\ t\geqslant T,$$

where the wave-train commences at $t=0$, and is interrupted by a collision at $t=T$. Submitting this damped and interrupted wave train to a Fourier analysis we find

$$x(t)=2x_0\int_0^\infty d\nu\int_0^T e^{-\frac{\gamma_0}{2}\tau}\cos 2\pi\nu_0\tau\times\cos 2\pi\nu(\tau-t)d\tau$$

$$=x_0\int_0^\infty\left[\frac{1+e^{-\gamma_0 T}-2e^{-\frac{\gamma_0}{2}T}\cos 2\pi(\nu-\nu_0)T}{4\pi^2(\nu-\nu_0)^2+\left(\frac{\gamma_0}{2}\right)^2}\right]^{\frac{1}{2}}\cos(2\pi\nu t-\psi)d\nu$$

neglecting as before terms with $(\nu+\nu_0)^2$ in the denominator. The intensity of the homogeneous wave-train with a frequency between ν and $\nu+d\nu$ will be proportional to the square of the amplitude of that component, that is proportional to the expression in square brackets. If T_0 is the average time between collisions, then the fraction of the number of collisions between T and $T+dT$ will be

$$\frac{1}{T_0}e^{-T/T_0}dT.$$

Hence the average intensity of the homogeneous wave-train with frequency between ν and $\nu+d\nu$ will be given by

$$\bar{I}_\nu d\nu=\frac{Kd\nu}{4\pi^2(\nu-\nu_0)^2+\left(\frac{\gamma_0}{2}\right)^2}\int_0^\infty\frac{1}{T_0}e^{-T/T_0}\left[1+e^{-\gamma_0 T}-2e^{-\frac{\gamma_0}{2}T}\cos 2\pi(\nu-\nu_0)T\right]dT$$

$$=I_0\frac{2\left(\frac{\gamma_0}{2}+\frac{1}{T_0}\right)d\nu}{4\pi^2(\nu-\nu_0)^2+\left(\frac{\gamma_0}{2}+\frac{1}{T_0}\right)^2}=I_0\frac{\delta_0+\delta_c}{\pi}\frac{d\nu}{(\nu-\nu_0)^2+(\delta_0+\delta_c)^2} \qquad (5)$$

where I_0 is the total intensity of the emission line, $\delta_c=1/2\pi T_0$ and as before $\delta_0=\gamma_0/4\pi$. The collisional half half-width is therefore added to the damping half half-width, and a greatly broadened line may be produced by the classical oscillator if T_0 is sufficiently small, that is if the impact diameter of the oscillator is sufficiently large. Since T_0 decreases linearly with the pressure, the collisional half half-width must increase linearly with the pressure.

Are these characteristics of the emission and absorption lines of the classical oscillator actually observed? The line given by the classical oscillator is excited under the same conditions as is the resonance line of an actual quantum-atom, so that observation of a resonance line should provide a test. In a classical experiment Minkowski * observed the resonance D-lines produced by *Na* vapour in a metre-long absorption tube backed by a continuous source. With a Rowland concave grating used in the second order and having a practical resolving power of the order of 120,000, he found the profiles of the two absorption lines by accurate photographic spectrophotometry. A determination of the equivalent number of classical oscillators by magneto-rotation enabled him

* R. Minkowski, *Z. Phys.*, **36**, 839, 1926.

to calculate the half half-width of the greatly broadened lines produced by the long column of absorbing vapour. For pressures below 0·0087 mm. the half half-width of both lines was found to be 0·000058 A., in excellent agreement with the damping half half-width given in equation (3). Above this pressure the half half-width was greater than the damping value, clearly indicating the onset of Lorentz collisional-broadening.

1.2. *The Quantum-Atom — Natural Line Width.*—Minkowski's results, confirmed by those of many other workers, show that there are properties of the quantum-atom additional to those originally postulated by Bohr. Two steps are required to incorporate the behaviour of the classical oscillator into that of the quantum-atom. First consider a cylinder of unit cross-section and small thickness dz containing $\tilde{N}$ classical oscillators per cm.^{3}. If $I_\nu d\nu d\omega$ is the flux normally incident on the face of this cylinder within a solid angle $d\omega$, then the loss of flux per unit solid angle due to absorption of the classical oscillators will be

$$dI_\nu d\nu = -\tilde{N}\alpha_\nu I_\nu d\nu dz,$$

where α_ν, the absorption coefficient for a single classical oscillator, is given by equation 1.1 (4) as

$$\alpha_\nu d\nu = \frac{\pi\epsilon^2}{mc}\frac{\delta_0}{\pi}\frac{d\nu}{(\nu-\nu_0)^2+\delta_0^2}. \tag{6}$$

The total energy lost in the cylinder, integrating over all frequencies, will thus be

$$dI_\nu = \int_0^\infty (dI_\nu)d\nu = -\tilde{N}\frac{\pi\epsilon^2}{mc}I_\nu dz, \tag{7}$$

a somewhat remarkable result since the half half-width, δ_0, has disappeared. Next consider a geometrically identical cylinder, only now containing per cm.^{3} N_1 quantum-atoms in the ground state; by a transition from state 1 to state 2 these atoms can absorb a quantum $h\nu_0$ of radiation of the same mean frequency as that absorbed by the classical oscillators. Introducing the atomic Einstein-coefficient, B_{12}, where the number of transitions upwards per unit time is

$$\frac{dN_1}{dt} = -N_1 B_{12} u_\nu,$$

u_ν being the energy density of the radiation field, we find the total loss of flux per unit solid angle due to transitions from state 1 to 2, each absorbing the quantum $h\nu_0$, to be

$$dI_\nu = -N_1 B_{12} h\nu_0 \frac{I_\nu}{c} dz. \tag{8}$$

Equating the right-hand sides of (7) and (8), and assuming one quantum-atom equivalent to f classical oscillators, that is $\tilde{N} = N_1 f$, we get

$$N_1 f \frac{\pi\epsilon^2}{mc} = N_1 \frac{h\nu_0}{c} B_{12}\ ;\ f = \frac{mh\nu_0}{\pi\epsilon^2} B_{12} = \frac{1}{3}\frac{q_2}{q_1}\frac{A_{21}}{\gamma_0}. \tag{9}$$

This value of f, the classical oscillator strength, required to make the total absorption of the quantum-atoms equal to that of the classical oscillators, is found from the well-known relation between B_{21} and A_{21}, defined by $\frac{dN_2}{dt} = -N_2 A_{21}$, namely

$$\frac{A_{21}}{B_{12}} = \frac{q_1}{q_2}\frac{8\pi h\nu^3}{c^3}, \tag{10}$$

where q_1, q_2 are the statistical weights of states 1, 2, and from the value of the classical damping constant given by equation 1.1 (1).

The second step is so to modify the quantum-atom as to give the line width. Since Bohr's frequency condition requires that the quantum $h\nu$ emitted or absorbed is equal to the difference of the energies of the two states concerned, it follows that a broadened line can only originate from transitions between broadened stationary states. It is, however, already clear from the uncertainty-principle, $\tau\Delta E \sim h/2\pi$, where τ is the life-time in the state, that the shorter the life-time, the greater must be the range of energy covered by the state. From the definition of the Einstein coefficient A_{21}, it follows that the average life-time in state 2 must be

$$\tau=\int_0^{N_2} tdN_2 \Big/ \int_0^{N_2} dN_2=\int_0^{\infty} tA_{21}e^{-A_{21}t}dt \Big/ \int_0^{\infty} A_{21}e^{-A_{21}t}dt=1/A_{21},$$

and from Wien's canal-ray experiments and from quantum mechanical calculations this is known to be of the order of 10^{-8} sec. Hence we may expect the excited states to be broadened, but the ground state, where the atom remains undisturbed for long periods of time, to be infinitely narrow. The resonance line of the quantum-atom, which bears so close a resemblance to the line emitted or absorbed by the classical oscillator, must therefore result from a transition between an infinitely narrow ground state and a broadened upper state. Let $W(E_2)dE_2$ be the probability that an atom in the broadened state 2 lies in a sub-level with an energy between E_2 and E_2+dE_2, and let a_{21}, b_{21}, and b_{12} be microscopic transition coefficients between the sub-levels of state 2 and the infinitely narrow state 1, where in accordance with Einstein's derivation of Planck's law

$$\frac{a_{21}}{b_{21}}=\frac{8\pi h\nu^3}{c^3} \; ; \; q_1 b_{12}=q_2 W(E_2)dE_2 \times b_{21}.$$

What form must the probability distribution $W(E_2)dE_2$ take in order that the quantum-atom will give the same absorption as the classical oscillator? Considering again our cylinder of thickness dz the flux absorbed will be per unit solid angle

$$N_1 f\alpha_\nu d\nu \times I_\nu dz=N_1\frac{h\nu}{c}b_{12}I_\nu dz=N_1\frac{h\nu}{c}\frac{q_2}{q_1}W(E_2)dE_2\frac{c^3}{8\pi h\nu^3}a_{21}\times I_\nu dZ,$$

where the left-hand side is the absorption for the $\tilde{N}=N_1 f$ classical oscillators and the right-hand side is the corresponding quantity for the actual quantum-atoms with the broadened upper state 2. Substituting the values of α_ν and f from equations (6) and (9), we find

$$W(E_2)dE_2=\frac{\delta}{\pi}\frac{1}{(\nu-\nu_0)^2+\delta^2}\frac{A_{21}}{a_{21}}d\nu.$$

Since by Bohr's frequency condition $h\nu=E_2-E_1 : h\nu_0=E_2^0-E_1$ it follows that

$$W(E_2)dE_2=\frac{\delta}{\pi}\frac{dE_2/h}{\left(\frac{E_2-E_2^0}{h}\right)^2+\delta^2}\frac{A_{21}}{a_{21}},$$

But

$$A_{21}=\int_0^{\infty} a_{21}W(E)_2dE_2=a_{21}\int_0^{\infty} W(E_2)dE_2=a_{21}$$

if we assume by analogy with the sum rule for multiplets that a_{21} is the same for all sub-levels of state 2. Hence

$$W(E_2)dE_2=\frac{\delta}{\pi}\frac{dE_2/h}{\left(\frac{E_2-E_2^0}{h}\right)^2+\delta^2}, \qquad (11)$$

where

$$\int_0^\infty W(E_2)dE_2=1$$

as it should.

From the derivation of equation (11) it follows that $\delta=\gamma_0/4\pi$, the half half-width of the line emitted or absorbed by the classical oscillator. The mean time, τ_0, of dying-away of the radiation emitted by the classical oscillator is

$$\tau_0=\int_0^\infty te^{-\gamma_0 t}dt\Big/\int_0^\infty e^{-\gamma_0 t}dt=1/\gamma_0,$$

so that if we equate the mean life-time in the excited state with the mean time of dying-away for the classical oscillator, it follows that the value of δ in our expression (11) is $\delta=A_{21}/4\pi$. This may agree with the classical value δ_0, as is the case for the *Na* D-lines in Minkowski's experiment, but need not necessarily do so. From this definition of the δ occurring in (11), it follows for a state $j>2$ that

$$\delta=\sum_{i=1}^{j-1}A_{ji}/4\pi,$$

where the summation is to be carried out over all lower states i for which transition from j are possible.

This elementary formulation of the complete quantum-mechanical theory of line broadening, due to Weisskopf and Wigner*, is sufficient to enable us to understand how in the actual quantum-atom the width of the line arises from the width of the upper state—a width which is inversely proportional to the life-time in that state.

When we come to consider lines which originate from transitions between two broadened levels, say i and j, the problem becomes slightly more complicated. By a further application of the process used in deriving an expression for $W(E_2)dE_2$ we find that the values of the microscopic transition coefficients for this problem are

$$\left.\begin{aligned} a_{ji}&=A_{ji}W(E_i)dE_i,\\ b_{ji}&=B_{ji}W(E_i)dE_i,\\ b_{ij}&=B_{ij}W(E_j)dE_j. \end{aligned}\right\} \qquad (12)$$

Now let us suppose the level j to be naturally excited, that is the distribution of atoms among the sub-levels of j is to be given by $W(E_j)$. Then the intensity of frequency ν given by a transition between a definite sub-level in j and a definite sub-level in i will be

$$h\nu\times N_k W(E_j)dE_j\times a_{ji}=N_j A_{ji}h\nu W(E_i)dE_i\times W(E_j)dE_j.$$

The total intensity of this component of the line will be found by integrating this expression over all values of E_j, subject to the condition that $E_j-E_i=h\nu$ is a constant. The resulting intensity-distribution in the emission line is found to be

$$I_\nu d\nu=\frac{h\nu}{4\pi}N_j A_{ji}\,\frac{\delta_i+\delta_j}{\pi}\,\frac{d\nu}{(\nu-\nu_0)^2+(\delta_i+\delta_j)^2}, \qquad (13)$$

or the half half-width is the sum of the half half-widths of the two levels concerned. The same result is true for the absorption coefficient when the lower level, i, is naturally excited. When the initial level is not naturally excited the problem becomes even more complicated, but has been solved by Spitzer.† Thus in the simple case of monochromatic absorption from the broadened i level, but far from the centre, the resultant

* V. Weisskopf and E. Wigner, *Z. Phys.*, **63**, 54, 1930; V. Weisskopf, *Observatory*, **56**, 291, 1933.
† L. Spitzer, *M.N.*, **96**, 794, 1936.

transition from j to i gives rise to two emission components.* This is an example of so-called non-coherent scattering, which as Houtgast† has observationally shown, probably plays a large part in the formation of solar absorption lines.

1.3. *The Quantum-Atom—Doppler Width.*—So far we have treated the quantum-atom, and equally the classical oscillator, as being at rest. If the atom is in motion in the line of sight with the velocity u, the central frequency ν_0 of the absorption coefficient will be displaced by Doppler effect to $\nu_0 - \frac{u}{c}\nu_0$. If $\phi(u)du$ is the fraction of atoms with a velocity between u and $u+du$ in the line of sight, then in thermodynamical equilibrium by Maxwell's law

$$\phi(u)du = \left(\frac{M}{2\pi kT}\right)^{\frac{1}{2}} e^{-Mu^2/2kT}du,$$

where M is the mass of the atom and k is Boltzmann's constant. The atomic absorption coefficient will then be obtained by averaging over all possible velocities, or

$$\alpha_\nu = \frac{\pi\epsilon^2}{mc} f \int_{-\infty}^{\infty} \phi(u) \frac{\delta}{\pi} \frac{du}{\left(\nu - \nu_0 + \frac{u}{c}\nu_0\right)^2 + \delta^2} = \frac{\pi\epsilon^2}{mc} f \frac{1}{b\sqrt{\pi}} \left[e^{-\omega^2} - \frac{2\delta}{b\sqrt{\pi}} (1 - 2\omega F(\omega)) \right],$$

where

$$b = \sqrt{\frac{2kT}{M}} \frac{\nu_0}{c} : \omega = \frac{\nu - \nu_0}{b} : F(\omega) = e^{-\omega^2} \int_0^{\omega} e^{\omega^2} d\omega,$$

an expression first derived by Voigt. It will be noted that ω is simply $(\nu - \nu_0)$ expressed in units of b, while b itself is a measure of the width of the line due to Doppler effect alone. Under stellar conditions b has values between 0·01 A. and 0·1 A. A useful approximation to this expression for the absorption coefficient is given by

$$\alpha_\nu = \frac{\pi\epsilon^2}{mc} f \frac{1}{b\sqrt{\pi}} \left[e^{-\omega^2} + \frac{\delta}{b\sqrt{\pi}} \frac{1}{\omega^2} \right]. \qquad (14)$$

The first term of this expression is to be used for small values of $\omega = \frac{\nu - \nu_0}{b}$, while for large values only the second term is to be used. The absorption coefficient consists therefore of an error-curve core, and outside of this core the natural line-widening takes charge giving wings decreasing as $(\nu - \nu_0)^{-2}$. It should be noted that Doppler widening also results in non-coherent scattering ‡, the absorbed quantum and the subsequently emitted quantum having different frequencies except under very restrictive circumstances.

1.4. *The Quantum-Atom—Impact-Width.*—Weisskopf § has shown from a quantum-mechanical calculation that the effect of impacts on the quantum-atom will be to produce exactly the same form of broadening as found by Lorentz for the classical oscillator. A similar conclusion had been reached earlier by Lenz from the correspondence-principle. It is clear, however, that the actual mechanism must be very different, since Bohr's frequency condition requires that the frequency absorbed or emitted is determined by the energies of the two levels concerned. It must therefore be supposed that the emitting or absorbing atom and the perturber form, during the time of the

* V. Weisskopf, *Observatory*, **56**, 291, 1933.
† J. Houtgast, Dissertation, Utrecht, 1942.
‡ L. G. Henyey, *Proc. Nat. Acad. Sc.*, **26**, 50, 1940.
§ V. Weisskopf, *Z. Phys.*, **75**, 287, 1932 ; *Phys. Z.*, **34**, 9, 1933.

collision, a single system, giving rise to a continuum of energy levels. For a time of collision short in comparison with the life-time in the excited state, this continuum will be different for the process of absorption and the subsequent process of emission, so that once again we shall get non-coherent scattering.

Impact-broadening, which is correctly given equally by the Lorentz theory and by quantum-mechanics, both of which lead to equation 1.1 (5), implies on the Lorentz theory an interruption of the wave-train by the collision, or a quenching of the radiation as by a collision of the second kind. It is well known from experiment, however, that impact-broadening can occur in the absence of quenching. To meet this difficulty Lenz * points out that a small percentage change in the 10^{-15} sec. period of the emitted radiation, produced by the perturbing field of the colliding atom during the average 10^{-13} sec. which the collision lasts, will be sufficient to produce a large change of phase between the wave-trains emitted before and after collision. Such non-coherent wave-trains act on Fourier analysis in precisely the same way as interrupted wave-trains, so that Lorentz or impact-broadening can occur in the absence of quenching. The impact diameter for such broadening is therefore that distance between the centres of the colliding atoms for which the perturbing field produces a perceptible change of phase. Weisskopf † arbitrarily takes a phase shift of unity as sufficient to produce non-coherent wave-trains, so that if $\Delta\nu(r)$ is the change of frequency when the perturber is at a distance r, then

$$\psi = \int_{-\infty}^{\infty} 2\pi\Delta\nu(r)dt \doteq 1.$$

If σ is the impact diameter and $\bar{v}$ the mean relative velocity of the colliding particles, then for a straight-line trajectory of the perturber

$$r = \sqrt{\bar{v}^2t^2 + \sigma^2}.$$

Two cases may now be distinguished. When the collisions are between identical oscillators or atoms we get a perturbation produced by dipole-interaction, so that

$$\Delta\nu(r) = \frac{C}{r^3},$$

where $C = \dfrac{\epsilon^2}{16\pi^2 m\nu_0} f$. Hence

$$\psi = \int_{-\infty}^{\infty} \frac{2\pi C dt}{(\bar{v}^2t^2+\sigma^2)^{\frac{3}{2}}} \doteq 1, \quad \text{or} \quad \sigma \doteq \sqrt{\frac{4\pi C}{\bar{v}}}. \tag{15}$$

When the collisions are between the radiating atom and a foreign atom, as generally holds in stellar atmospheres, the perturbing field is produced by Van der Waals's forces, so that

$$\Delta\nu(r) = \frac{C}{r^6}$$

and

$$\psi = \int_{-\infty}^{\infty} \frac{2\pi C dt}{(\bar{v}^2t^2 + \sigma^2)^3} \doteq 1, \quad \text{or} \quad \sigma \doteq \sqrt[5]{\frac{6\pi^2 C}{8}}\,\frac{1}{\bar{v}}. \tag{16}$$

In both these cases we know that the collisional half half-width is given by

$$\delta_c = \frac{1}{2\pi T_0},$$

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* W. Lenz, *Z. Phys.*, **25**, 299, 1924.

† V. Weisskopf, *Z. Phys.*, **75**, 287, 1932.

where from the kinetic theory the mean time, T_0, between collisions is

$$\frac{1}{T_0} = 2\sigma^2 N \sqrt{2\pi kT \times \frac{M_1 + M_2}{M_1 M_2}},$$

M_1 and M_2 being the masses of the colliding atoms, and N the number of atoms per unit volume. Hence

$$\delta_c = \frac{\sigma^2 N}{\pi} \sqrt{2\pi kT \times \frac{M_1 + M_2}{M_1 M_2}} \qquad (17)$$

from which we may either find δ_c from the value of σ given by (15) or (16), or alternatively can compute the impact diameter from the observed half half-width, δ_c. Minkowski's observations, earlier described, of the collisional half half-width in a *Na* absorption tube give excellent agreement between the observed σ and that predicted from (15). Subsequently Minkowski * observed the collisional half half-width for *Na* in an atmosphere of argon, and found under certain conditions a value of σ of $7{\cdot}9 \times 10^{-8}$ cm. A calculation of σ from (16) by Weisskopf † gave upper and lower limits to its value of $7{\cdot}6 \times 10^{-8}$ cm. and 10^{-7} cm., a not unsatisfactory agreement in view of the difficulty of evaluating the quantity C in (16).

1.5. *The Quantum-Atom—Statistical Broadening and a Summary.*—Statistical broadening of the atomic absorption coefficient ‡ in its limiting form arises when the radiating atom and the perturbers are at rest. The probability that the nearest perturber lies in a spherical shell centred on the radiating atom at a distance between r and $r+dr$ may be shown to be

$$W(r)dr = e^{-(r/r_0)^3} d(r/r_0)^3,$$

where r_0 is the average distance between perturbers. Hence, when N is the number of perturbers per unit volume

$$\tfrac{4}{3}\pi r_0^3 N = 1.$$

If the displacement in frequency produced by a perturber is

$$\Delta\nu(r) = C/r^n,$$

then the normal displacement, $\Delta\nu_0$, will be given by

$$\Delta\nu_0 = C/r_0^n = C(\tfrac{4}{3}\pi N)^{n/3},$$

and in terms of $\Delta\nu_0$ the probability distribution will be

$$W(\nu)d\nu = e^{-(\Delta\nu_0/\Delta\nu)^{3/n}} \cdot \frac{3}{n} \left(\frac{\Delta\nu_0}{\Delta\nu}\right)^{\frac{3}{n}+1} \frac{d\nu}{\Delta\nu_0}.$$

If the radiating atom is subject to a linear Stark effect ($n=2$), as is for example hydrogen, then the nearest ion or electron with a charge of ϵ will produce a displacement

$$\Delta\nu = C/r^2 = C \,.\, F/\epsilon,$$

where F is the resulting field-strength. The normal field-strength, F_0, produced by a perturber at r_0, will clearly be

$$F_0 = \frac{\epsilon}{r_0^2} = \epsilon \left(\frac{4\pi}{3} N\right)^{\frac{2}{3}} = 2{\cdot}60\epsilon N^{\frac{2}{3}}.$$

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* R. Minkowski, *Z. Phys.*, **55**, 16, 1929.

† V. Weisskopf, *Phys. Z.*, **34**, 14, 1933.

‡ H. Margenau, *Phys. Rev.*, **40**, 387, 1932; H. Margenau and W. W. Watson, *Rev. Mod. Phys.*, **8**, 22, 1936.

From the theory of the linear Stark effect

$$C=\frac{3h}{8\pi^2 m}n_k,$$

where n_k is a quantum number. The original single line is thus split up into a number of components, and each component may be regarded as being smeared out in accordance with the probability-distribution given above. The resulting line profile will be found by adding these components, each weighted according to its theoretically known intensity. Reference may be made to the complete theory of Stark broadening given by Pannekoek and Verwey * where, following Holtsmark, the effect of ions or electrons, in addition to the nearest, is also included.

The difficult problem of deciding under what conditions the impact-broadening of Section 1.4 gives place to statistical broadening has been discussed by Burkhardt † and by Spitzer.‡ An analysis of their results, with special reference to stellar atmospheres, has been given by Unsöld § in the course of an admirable review of the problem of pressure-broadening. Apart from hydrogen where statistical broadening due to the linear Stark-effect ($n=2$) of ions is dominant, all other elements (with the possible exception of helium) show impact-broadening due primarily to van der Waals's forces ($n=6$).

Summarizing this lengthy discussion, the atomic line-absorption coefficient for a quantum-atom at rest, making transitions between the ground state and some higher state j, is given by

$$a_\nu d\nu=\frac{\pi\epsilon^2}{mc}f\frac{\delta+\delta_c}{\pi}\frac{d\nu}{(\nu-\nu_0)^2+(\delta+\delta_c)^2}, \tag{18}$$

where

$$\delta=\delta_j=\sum_{i=1}^{j-1}A_{ji}/4\pi, \text{ and } \delta_c=\frac{\sigma^2 N}{\pi}\sqrt{2\pi kT\times\frac{M_1+M_2}{M_1M_2}},$$

σ being the impact diameter which under ordinary astronomical conditions may be found from equation (16). If the transition takes place between two broadened levels, i and j, where state i is naturally excited, then $\delta=\delta_i+\delta_j$. When the atoms have a Maxwellian velocity distribution, the atomic line-absorption coefficient is approximately given by

$$a_\nu d\nu=\frac{\pi\epsilon^2}{mc}f\frac{1}{b\sqrt{\pi}}\left[e^{-\omega^2}+\frac{\delta}{b\sqrt{\pi}}\frac{1}{\omega^2}\right]d\nu, \tag{19}$$

where

$$b=\sqrt{\frac{2kT}{M}}\frac{\nu_0}{c}, \quad \omega=\frac{\nu-\nu_0}{b}.$$

2. *The Equation of Transfer*

2.1. *The General Equation.*—To apply our atomic line-absorption coefficient to find the number of atoms per unit volume in a gaseous medium, we must find a relation between the intensity at any frequency ν in the emergent radiation and the absorption and emission coefficients. Consider the flux of radiation emerging within an elementary solid angle $d\omega$ from an element of area $d\sigma$ on the boundary of the medium ; this is made up of the sum of the contributions, each weakened by the appropriate absorption, from

* A. Pannekoek and S. Verwey, *Proc. Amsterdam Acad.*, **38**, No. 5, 1935.
† G. Burkhardt, *Z. Phys.*, **115**, 592, 1940.
‡ L. Spitzer, *Phys. Rev.*, **58**, 348, 1940.
§ A. Unsöld, *V.J.S. Ast. Ges.*, **78**, 213, 1944.

the volume-elements of the medium which lie inside the cone of solid angle $d\omega$ on the medium-side of the vertex at $d\sigma$. Our first problem is therefore to find the gains and losses within one such volume-element in the medium, and this gives us the fundamental differential equation of transfer. Our second problem is to sum up the contributions from these volume-elements, that is to integrate the differential equation.

To find the equation of transfer, let us measure distance from the vertex of the cone into the medium by the coordinate r, the origin occurring at the vertex $d\sigma$. A volume-element of the gaseous medium at a distance r from the vertex will have a surface area $dS=r^2d\omega$, and a thickness dr, dr being small compared with dS. Let $I_\nu(r, \psi)$ be the specific intensity of the radiation field at the point r and in a direction making an angle ψ with the negative direction of r. The flux normally incident on the surface dS and proceeding so as to strike $d\sigma$ on the boundary will be

$$I_\nu(r, 0)d\nu\, dS\, \frac{d\sigma}{r^2}=I_\nu(r, 0)d\nu\, d\sigma\, d\omega.$$

The loss due to absorption in the thickness dr of the volume-element will be

$$(k_0+k_\nu)I_\nu(r, 0)d\nu\, d\sigma\, d\omega\, dr,$$

where k_0 is the coefficient of continuous absorption of frequency ν in the medium at the position r, and $k_\nu=N\alpha_\nu$ is the coefficient of line absorption at the same frequency and position. The gain in the flux proceeding to strike $d\sigma$ from the emission in the volume-element will be

$$(j_0+j_\nu)d\nu\, dS\, dr\frac{d\sigma}{r^2}=(j_0+j_\nu)d\nu\, d\sigma\, d\omega\, dr,$$

where j_0 and j_ν are respectively the coefficients of continuous and line-emission (flux per unit volume per unit solid angle). The net increase in flux in the direction of r decreasing will therefore be

$$dI_\nu(r, 0)d\nu\, d\sigma\, d\omega=[(k_0+k_\nu)I_\nu(r, 0)-(j_0+j_\nu)]d\nu\, d\sigma\, d\omega\, dr$$

or

$$\frac{dI_\nu(r, 0)}{dr}=(k_0+k_\nu)I_\nu(r, 0)-(j_0+j_\nu), \tag{1}$$

a differential equation which is valid for each volume-element of the medium lying inside the cone of solid angle $d\omega$ with a vertex at $d\sigma$ on the boundary.

The equation of transfer (1) is a non-homogeneous differential equation of the first order with a boundary condition given by the fact that there must be no radiation flowing into the surface element $d\sigma$ from outside the medium. Introducing an optical depth

$$t=\int_0^r(k_0+k_\nu)dr,$$

we can formally write down the solution of our differential equation in the form of an integral equation

$$I_\nu(0, 0)=I_\nu(t_1, 0)e^{-t_1}+\int_0^{t_1}\frac{j_0+j_\nu}{k_0+k}\,e^{-t}dt, \tag{2}$$

where for sufficiently large values of t_1, $I_\nu(t_1, 0)e^{-t_1}$ equals zero. It follows from (2) that to find the emergent intensity we must first know the coefficients of emission and absorption as functions of optical depth, that is we must know the numbers of atoms in the required stationary states as functions of depth. This, however, is the very information we hope to obtain as a result of astronomical spectroscopy, and we seem to have reached an impasse. The usual way out of this difficulty is to assume the stellar

atmosphere to be built on some simple model, that is to assume a specific mode of variation of the coefficients of emission and absorption as functions of optical depth. We may then carry out the integration indicated in (2), and from the observed intensity $I_\nu(0, 0)$ and the known values of the absorption and emission coefficients given in Section 1 we may find the numbers of atoms as functions of depth. If the results so obtained from a number of different absorption lines are consistent with each other and with the assumptions on which the model is based, we may feel confident that we have made a first step towards understanding the structure of the stellar atmosphere concerned.

2.2. *A Particular Form of Equation.*—Some of the difficulties involved in the integration of the equation of transfer disappear if the equation is simplified. The usual simplifying assumption is that of coherent scattering, that is the quantum of absorbed radiation is assumed to retain its identity while imprisoned by the atom, and ultimately to be re-emitted with its frequency unchanged. From our discussion in Section 1 we know that atoms do not behave this way, but in so difficult a problem it is justifiable to make this exploratory assumption. Let us commence by writing the coefficient of line emission in the form $j_\nu = j_\nu' + j_\nu''$. The first term, j_ν', is that part of the line-emission which results from atoms getting into the upper state of the line concerned by collisions of the first kind, by captures or by jumps from higher levels. If the atom which has thus got into the upper state now relapses to the lower state of the line concerned it will not necessarily, even on the assumption of coherent scattering, emit the same frequency as the one we are studying. In j_ν' we are, however, only concerned with the thus excited atoms which do emit this frequency. The second term, j_ν'' is that part of the line emission which results from the excitation of atoms to the upper state by absorption of the quantum $h\nu$ from the atoms in the lower state of the l ne concerned. Of these the fraction ϵ will suffer a collision of the second kind, or be otherwise prevented (by photo-ionization or by excitation to higher levels) from making a contribution to the line emission, while the fraction $1-\epsilon$ must necessarily emit, by the assumption of coherent scattering, a quantum of precisely the same frequency as that previously absorbed.

The term j_ν'' may be readily evaluated. Considering once again our elementary volume (Section 2.1) the flux incident on the face dS at an angle ψ with the normal and within the solid angle $d\Omega$ will be

$$I_\nu(r, \psi) d\nu \, dS \cos\theta d\Omega.$$

The energy absorbed will therefore be (since the thickness is $\sec\psi \times dr$)

$$k_\nu I_\nu(r, \psi) d\nu \, dS \, d\Omega \, dr.$$

Of the excited atoms so produced the fraction $1-\epsilon$ will spontaneously emit the quantum $h\nu$ and of these the fraction $\frac{\gamma(\psi)}{4\pi} \frac{d\sigma}{r^2}$ will emit their radiation in such a direction as to strike $d\sigma$. For isotropic scattering $\gamma(\psi) = 1$, while for scattering according to Rayleigh's law $\gamma(\psi) = \frac{3}{4}(1+\cos^2\psi)$; in either event $\int \gamma(\psi) \frac{d\Omega}{4\pi} = 1$. Hence the total useful flux emitted will be found by integrating over all directions, or

$$j_\nu'' \, d\nu \, d\sigma \, d\omega \, dr = (1-\epsilon) k_\nu \, d\nu \, d\sigma \, d\omega \, dr \int_{\text{sphere}} \gamma(\psi) I_\nu(r, \psi) \frac{d\Omega}{4\pi}.$$

It is usual to express the integral by the symbol J_ν, so that

$$j_\nu''=(1-\epsilon)k_\nu J_\nu.$$

If further the gaseous medium has a plane boundary and is stratified in layers plane-parallel to the boundary, we may introduce in place of r a new coordinate x measured inwards from $x=0$ at the boundary and normal to it. With this new coordinate the thickness dr of our volume-element will be given by $\sec\theta dx$, where θ is the angle between the outgoing direction and the negative direction of x. Our equation of transfer (1), with these new coordinates and on the assumption of coherent scattering, thus takes the form

$$\cos\theta\frac{dI_\nu(x,\theta)}{dx}=(k_0+k_\nu)I_\nu(x,\theta)-[j_0+j_\nu''+(1-\epsilon)k_\nu J_\nu]. \tag{3}$$

This form of the equation of transfer has a simple application to laboratory problems. Consider a tube of length x_1, such as that used by Minkowski, containing uniformly distributed atoms all in their ground state and backed by a source of continuous spectrum of specific intensity, or surface brightness, I_0 at the frequency ν. If the gas is cold, there is no continuous absorption or emission so that $k_0=j_0=0$; further, since there is no means whereby atoms may get into the excited state except by absorption of the quantum $h\nu$, we may put $j_\nu'=0$. The equation of transfer thus takes the form

$$\cos\theta\frac{dI_\nu(x,\theta)}{dx}=k_\nu I_\nu(x,\theta)-(1-\epsilon)k_\nu J_\nu. \tag{4}$$

Let us assume that the excited atoms are all de-excited by collisions of the second kind so that $\epsilon=1$. Then on integration of (4) we get for the emergent intensity in the line

$$I_\nu(0,\theta)=I_0e^{-k_\nu x_1\sec\theta}. \tag{5}$$

This is the usual exponential law of absorption, the absorbed energy being used to heat up the gas. This result is also nearly true when $\epsilon=0$ (pure scattering), provided an approximately parallel beam from the continuous source passes through the tube. This follows because the fraction of scattered radiation which gets into the small solid angle of the approximately parallel beam is itself very small. An exact treatment of this not simple problem for purely scattered radiation is given by Milne *, only with different boundary conditions, in his paper on planetary nebulae.

2.3. *Eddington's Equation of Transfer.*—In a stellar atmosphere, which may be reduced to a plane-parallel layer problem, we have a gas composed of atoms of different ionization potentials and free electrons, through which passes a flux of radiation from the interior of the star. Each volume-element of the gas gives rise to continuous absorption and emission due to photo-ionization and recombination of the atoms of low ionization potential and due to free-free electron switches, and also to line absorption and emission of the atoms in which we are interested when we study a particular absorption line. Eddington † was the first to apply the simplified equation of transfer (3) to this problem. Not only did this imply, as he was careful to point out, coherent scattering, but he introduced explicitly the additional assumptions that $j_\nu'=0$ (atoms excited only by the absorption of the quantum $h\nu$) and that $\gamma(\psi)=1$ (isotropic scattering). If the atmosphere is in local thermodynamic equilibrium we may put the coefficient of continuous emission, $j_0=(k_0+\epsilon k_\nu)B_\nu$, where B_ν is the specific intensity of black-body radiation

* E. A. Milne, *Z. Astrophys.*, **1**, 98, 1930.
† A. S. Eddington, *M.N.*, **89**, 620, 1929.

given by Planck's law for the temperature T appropriate to the depth x in the atmosphere. With these assumptions Eddington wrote equation (3) in the form

$$\cos\theta \frac{dI_\nu(x,\theta)}{dx} = (k_0+k_\nu)I_\nu(x,\theta) - (k_0+\epsilon k_\nu)B_\nu(x) - (1-\epsilon)k_\nu J_\nu(x). \tag{6}$$

An equation of transfer of this form was applied by Milne * to a quite different problem in stellar atmospheres, and he was the first to integrate it ; consequently (6) is sometimes described as the Milne-Eddington equation.

Commencing with Milne the approximate integration of this equation of transfer has been effected in a variety of ways. One of the most useful, since it allows for arbitrary variations with x of the quantities k_ν/k_0 and $(1-\epsilon)k_\nu J_\nu$, is due to Strömgren.† Following Eddington he assumes that the specific intensity of the radiation-field may be represented by

$$I_\nu(x,\theta) = a + b\cos\theta + c\cos^3\theta + \ldots,$$

and introduces the symbols

$$J_\nu(x) = \int_{\text{sphere}} I_\nu(x,\theta)\frac{d\omega}{4\pi}\,; \quad F_\nu(x) = \int_{\text{sphere}} I_\nu(x,\theta)\cos\theta\,\frac{d\omega}{\pi}\,; \quad K_\nu(x) = \int_{\text{sphere}} I_\nu(x,\theta)\cos^2\theta\frac{d\omega}{4\pi}.$$

Of these $\pi F_\nu(x)$ is the net flux across unit area in the stellar atmosphere, and $F_\nu(0)$ is the net flux per unit solid angle at the boundary ; the latter is also equal to the average surface brightness of the hemisphere of the star exposed to the observer. If we now multiply equation (6) though by $d\omega$ and by $\cos\theta\, d\omega$ respectively and integrate over the sphere we get

$$\frac{d\frac{1}{4}F_\nu(x)}{dx} = (k_0+\epsilon k_\nu)(J_\nu - B_\nu)\,; \quad \frac{dK_\nu(x)}{dx} = (k_0+k_\nu)\frac{F_\nu(x)}{4}. \tag{7}$$

Introduce an optical depth defined by $\tau_\nu = \int_0^x (k_0+k_\nu)dx$, as well as the symbols $\eta = k_\nu/k_0$ and $\lambda = \frac{1+\epsilon\eta}{1+\eta}$. By virtue of our definition of J_ν and K_ν, and the assumption about the angular dependence of $I_\nu(x,\theta)$, it follows that $K_\nu = \frac{1}{3}J_\nu$. Hence equations (7) become

$$\frac{d^2J_\nu}{d\tau_\nu^2} = 3\lambda(J_\nu - B_\nu). \tag{8}$$

This non-homogeneous second order differential equation, apart from the assumption about the angular dependence of $I_\nu(x,\theta)$, is exactly equivalent to the equation of transfer (6) ; in particular no assumption has yet had to be made about the dependence of λ and B_ν upon optical depth τ_ν. To find the specific intensity at any frequency in the emergent absorption line we must integrate (8) subject to two boundary conditions. First in the deep interior as $\tau_\nu \to \infty$, $J_\nu - B_\nu$ must not increase exponentially, and secondly at $\tau_\nu = 0$ there must be no flux of radiation from outside the star. Following Eddington it is assumed that $I_\nu(0,\theta) = a$, a constant, so that this second boundary condition can be expressed in the form $J_\nu(0) = \frac{1}{2}F_\nu(0)$.

Subject to these boundary conditions Strömgren now proceeds to integrate (8) by the method of variation of parameters. For our immediate purpose it will, however, suffice to consider the simplest model atmosphere where λ, that is η and ϵ are each independent of optical depth. From the theory of a stellar atmosphere in radiative

* E. A. Milne, *Phil. Trans.*, A, **223**, 237, 1922.
† B. Strömgren, *Ap. J.*, **86**, 1, 1937.

equilibrium it is known that B_ν is with sufficient accuracy a linear function of the optical depth $\tau_0=\int_0^x k_0 dx$ in the continuous spectrum, or $B_\nu=B_0(1+\beta\tau_0)$. Since by virtue of our assumptions about the constancy of the absorption coefficients with depth

$$\frac{\tau_0}{\tau_\nu}=\frac{k_0\int dx}{(k_0+k_\nu)\int dx}=\frac{1}{1+\eta},$$

it follows that $B_\nu=B_0\left(1+\frac{\beta}{1+\eta}\tau_\nu\right)$, where B_0 and β are known when the effective temperature of the star and the variation of k_0 with frequency are known. Our equation (8) may therefore be written

$$\frac{d^2(J_\nu-B_\nu)}{d\tau_\nu^2}=3\lambda(J_\nu-B_\nu),$$

and on integration subject to the two boundary conditions we find the average surface brightness, $F_\nu(0)$, at the frequency ν in the line to be

$$F_\nu(0)=\tfrac{4}{3}B_0\frac{\sqrt{3\lambda}+\beta/(1+\eta)}{1+2\sqrt{3\lambda}/3}.$$

The average surface brightness, $F_0(0)$, at the same frequency in the continuous spectrum, where $\eta=0$ and $\lambda=1$, will be

$$F_\nu(0)=\tfrac{4}{3}B_0\frac{\sqrt{3}+\beta}{1+2\sqrt{3}/3}.$$

Hence the ratio of intensity, r_ν, in the line to that in the adjacent continuous spectrum will be

$$r_\nu=\frac{F_\nu(0)}{F_0(0)}=\frac{\sqrt{3\lambda}+\beta/(1+\eta)}{\sqrt{3}+\beta}\times\frac{1+\frac{2}{3}\sqrt{3}}{1+\frac{2}{3}\sqrt{3\lambda}}. \tag{9}$$

When $\epsilon=0$, that is when there are no collisions of the second kind, and when $\eta\ll 1$, Unsöld * has shown that (9) may be written in the form

$$r_\nu=1-\frac{\eta}{2}\left[\frac{1}{1+2/\sqrt{3}}+\frac{1}{1+\sqrt{3}/\beta}\right], \tag{10}$$

an interesting result since the strength of the absorption line is seen to depend upon $\eta=k_\nu/k_0$—the larger k_0 the weaker the absorption line. Equation (10) may also be written in the form

$$r_\nu=1-\mu N a_\nu, \tag{11}$$

giving the required dependence of the observed intensity ratio, r_ν, upon the atomic absorption coefficient (equation 1.5 (19)) and the number of atoms per unit volume. In this expression the quantity μ clearly depends upon the continuous absorption coefficient, k_0, and certain known constants. Equation (11) also applies to a line formed in pure absorption $\epsilon=1$, only with a different definition of the constant part of μ.

3. *The Curve of Growth*

3.1. *Equivalent Width.*—The ideal, still far short of attainment, in astronomical spectroscopy must be the construction of spectroscopes with practical resolving power of at least 10^6. From the accurate profiles determined with such instruments, and from the atomic line-absorption coefficient introduced into the integrated equation of transfer,

* A. Unsöld, *Physik der Sternatmosphären*, p. 241, 1938.

each absorption line would yield three physically significant parameters. First from the Doppler-core of the line would be determined the quantity b, giving the kinetic temperature of thermal agitation of the atom concerned. Secondly from the line wings would be found the half half-width, $\delta+\delta_r$, from which, knowing the radiation damping half half-width δ, δ_r and with it the optical impact diameter, σ, could be ascertained. Finally from the intensity ratio, r_ν, at any frequency in the line, given the oscillator strength and the previously determined parameters, the ratio of the number of atoms in the lower state to the continuous absorption coefficient could be found. Unfortunately existing spectroscopes fall far short of this ideal, and even the large solar instruments have practical resolving powers less than 2×10^5. The result is that at present the profiles of only a few strong lines (Rowland number >5) can be determined in the solar spectrum, and they only with moderate precision.* For stellar spectra the situation is correspondingly worse since the faintness of star-light makes the use of powerful spectroscopes impossible.

Pending the design and construction of the powerful spectroscope of the future, it is fortunate that in the meantime much can be learned from the equivalent width of an absorption line. From the conservation of energy it is evident that the spectroscope can influence in no way the total energy which has been absorbed in the line, so that the quantity

$$\int_0^\infty (F_0(0)-F_\nu(0))d\nu=F_0(0)\int_0^\infty (1-r_\nu)d\nu$$

is the same for all spectroscopes. The equivalent width

$$W_\nu=\int_0^\infty (1-r_\nu)d\nu \tag{1}$$

has the dimensions of a frequency, and is a convenient expression for the total energy lost in the line expressed in units of $F_0(0)$, the average surface brightness in the adjacent continuous spectrum. Equivalent widths are generally expressed in angstroms, where

$$\frac{W}{\lambda}=\frac{W_\nu}{\nu}.$$

W, the equivalent width in angstroms, is therefore the width of a rectangular profile of zero central intensity which absorbs the same total energy as the actual profile.

3.2. *The Theoretical Curve of Growth.*—For the purpose of astronomical spectroscopy we now require the functional relation between the equivalent width of the line on the one hand and the number of atoms and the half half-width on the other. Such a relation is known as the curve of growth, and in giving its theory I shall follow the work of Menzel†, merely noting that an equivalent treatment has been given by Unsöld ‡ which requires, however, the determination of an additional parameter from the line profile, and at that one which is very difficult to find even with the best existing spectroscopes. From equation 2.3 (11) the intensity ratio in the absorption-line is given by

$$r_\nu=1-\mu N\alpha_\nu=\frac{1}{1+\mu N\alpha_\nu}, \tag{2}$$

which involves the assumption that the greatly extended line wings, where α_ν is small, effectively determine the equivalent width of the line. From the value of α_ν in equation

* R. O. Redman, *M.N.*, **98**, 325, 1938.
† D. H. Menzel, *Ap. J.*, **84**, 462, 1936 ; *Pop. Astr.*, **47**, 6, 66, 124, 1939.
‡ A. Unsöld, *Physik der Sternatmosphären*, p. 264, 1938.

(1.5) (19), putting

$$X_0=\mu\frac{\pi\epsilon^2}{mc}Nf\frac{1}{b\sqrt{\pi}}, \tag{3}$$

we find the equivalent width to be given by

$$W_\nu=\int_0^\infty(1-r_\nu)d\nu=\int_0^\infty\frac{d\nu}{1+\left[X_0\left(e^{-\omega^2}+\frac{\delta}{b\sqrt{\pi}}\frac{1}{\omega^2}\right)\right]^{-1}}.$$

Changing the variable of integration to $\omega=\frac{\nu-\nu_0}{b}$ and putting $b=\frac{\nu_0}{c}v$, where $v=\sqrt{\frac{2kT}{M}}$, we get (since the integrand is an even function of ω)

$$\frac{W_\nu}{\nu_0}=2\frac{v}{c}\int_0^\infty\frac{d\omega}{1+\left[X_0\left(e^{-\omega^2}+\frac{\delta}{b\sqrt{\pi}}\frac{1}{\omega^2}\right)\right]^{-1}}=\frac{W}{\lambda}. \tag{4}$$

As it stands the integral cannot be evaluated analytically, and we are forced to carry out numerical integrations for varying values of X_0. Taking advantage, however, of the conditions under which equation 1.5 (19) is valid we may treat analytically certain limiting cases.

(i) $X_0<1$, i.e. few atoms per unit volume. Then

$$\frac{W}{\lambda}=\frac{2v}{c}\int_0^\infty\frac{d\omega}{1+1/X_0e^{-\omega^2}}\doteq\sqrt{\pi}\frac{v}{c}X_0. \tag{5}$$

(ii) $X_0>1$, i.e. more atoms per unit volume, but not so many that the damping wings need be considered. Then by an asymptotic expansion

$$\frac{W}{\lambda}=\frac{2v}{c}\int_0^\infty\frac{d\omega}{1+1/X_0e^{-\omega^2}}\doteq\frac{2v}{c}(lnX_0)^{\frac{1}{2}}. \tag{6}$$

(iii) $X_0\gg1$, i.e. so many atoms that the Doppler-core may be neglected. Then

$$\frac{W}{\lambda}=\frac{2v}{c}\int_0^\infty\frac{d\omega}{1+\left(X_0\frac{\delta}{b\sqrt{\pi}}\right)^{-1}\omega^2}=\pi^{\frac{3}{4}}\sqrt{X_0\frac{v}{c}\frac{\delta}{\nu_0}}. \tag{7}$$

Taking logarithms of both sides in the limiting cases (i) and (iii) we see that

$$\log\left(\frac{W}{\lambda}\frac{c}{v}\right)=\tfrac{1}{2}\log\pi+\log X_0, \tag{8}$$

$$\log\left(\frac{W}{\lambda}\frac{c}{v}\right)=\tfrac{3}{4}\log\pi+\tfrac{1}{2}\log\frac{\delta}{\nu_0}\frac{c}{v}+\tfrac{1}{2}\log X_0, \tag{9}$$

or the theoretical curve of growth, where $\log\frac{W}{\lambda}\frac{c}{v}$ is plotted against $\log X_0$, commences with a linear portion with a slope of unity (the Doppler-part), and ends with a second linear portion with a slope of one-half (the damping portion) whose intercept on the $\log\frac{W}{\lambda}\frac{c}{v}$ axis is determined by the half half-width. The intermediate portion of the curve, which is almost flat, originates in the nearly square-shouldered Doppler-core to the atomic line-absorption coefficient, so that after the Doppler-core is saturated an increase in the number of atoms per unit volume produces little change in the equivalent width. The onset of the flat part will clearly be fixed by the width of this Doppler-core, that is by the quantity b, or equivalently v.

3.3. *Numbers of Atoms and Excitation Temperatures.*—While Schütz * and van der Held † were the first to give the theory of the complete curve of growth for exponential absorption in the laboratory, it was our Medallist ‡ who first constructed an empirical curve of growth for the Sun. Following a suggestion of Russell, Adams and Moore §, he plotted for individual multiplets the logarithm of his measured equivalent widths against the logarithm of the relative oscillator strengths, the latter being taken from the theoretical intensities of the lines deduced from the sum-rule and the correspondence-principle (subsequently confirmed by quantum-mechanics). This gave him small sections of the empirical curve of growth, and these were united into a single curve by a legitimate sliding of the individual sections along the $(\log f)$ axis. As a result he was the first to establish empirically the wave-length dependence of the equivalent width, the theoretical interpretation of which is given, following Menzel, in the previous subsection, and the first to find the then surprising result that the half half-width of the line was some nine times greater than that predicted from natural line-widening.

The two outstanding recent discussions of the solar curve of growth have been by Menzel, Baker and Goldberg ‖ and by K. O. Wright.¶ The first authors used the accurate equivalent widths determined by Allen **, and for relative f-values the computations by Goldberg †† of the theoretical intensities of the multiplets as a whole in a transition array. The numerous lines in a complete array covered a large range in X_0, and thus allowed a very accurate determination of the empirical curve of growth. Considering the lines of a single element, the horizontal displacement of the various multiplets in the $\left(\log \frac{W}{\lambda}, \log X_0\right)$ diagram gave in effect the ratio of the number of atoms in the ground states of the multiplets, and hence from Boltzmann's law the excitation-temperature of the solar atmosphere. The vertical displacement of this empirical curve of growth to bring it into coincidence with the theoretical curve, in which $\log\left(\frac{W}{\lambda}\frac{c}{v}\right)$ is plotted against $\log X_0$, gives a determination of v, and so of the kinetic temperature of thermal agitation of the atoms, while the branch of the theoretical damping curve on which the empirical curve lies gives an average value for the half half-width of the lines. In this way Menzel, Baker and Goldberg found excitation-temperatures of 4150 ± 50 deg. K. for *Fe*, and 4350 ± 50 deg. K. for *Ti*, a value of v of 0·6 km. sec.$^{-1}$ corresponding to a kinetic temperature of 5740 deg. K., and half half-widths approximately ten times the radiation-damping value.

These surprisingly low excitation temperatures have been confirmed by the already cited investigation of K. O. Wright. In the construction of his curve of growth Allen's equivalent widths were again used, but supplemented by Wright's own measures of equivalent widths from our Medallist's invaluable *Atlas of the Solar Spectrum.*‡‡ No systematic difference was found between the equivalent widths from these two sources, while the accidental differences amounted to 7 per cent for lines with $W < 0{\cdot}05$ A.,

* W. Schütz, *Z. Phys.*, **64**, 682, 1930.
† E. F. M. v. d. Held, *Z. Phys.*, **70**, 508, 1931.
‡ M. Minnaert and G. F. W. Mulders, *Z. Astrophys.*, **1**, 192, 1930 ; **2**, 165, 1931.
§ H. N. Russell, W. S. Adams and C. E. Moore, *Ap. J.*, **68**, 1, 1928.
‖ D. H. Menzel, J. G. Baker and L. Goldberg, *Ap. J.*, **87**, 81, 1938.
¶ K. O. Wright, *Ap. J.*, **99**, 249, 1944.
** C. W. Allen, *Memoirs Commonwealth Solar Obs.*, **1**, No. 5, 1934.
†† L. Goldberg, *Ap. J.*, **82**, 1, 1935.
‡‡ M. Minnaert, G. F. W. Mulders and J. Houtgast, Amsterdam, 1940

and to less than 6 per cent for stronger lines. The distinguishing feature of Wright's curve of growth, however, is his use of relative f-values determined by R. B. and A. S. King * from vacuum-furnace spectra of *Fe* and *Ti*. Plots of Goldberg's theoretical f-values against the Kings's empirical values show systematic differences presumably due to failure of the Russell-Saunders's coupling assumed by Goldberg, a failure already indicated by the presence of intersystem-lines. With an empirical curve of growth so constructed Wright finds excitation-temperatures for *Ti* and *Fe* of 4550 deg. K. and 4850 deg. K. respectively, while by comparison with Menzel's theoretical curve of growth a value of v of 0·9 km.sec.$^{-1}$ (corresponding to a kinetic temperature of 13,000 deg. K.) and a half half-width fifteen times the radiation-damping value. The differences between the excitation-temperatures found by Menzel and his colleagues on the one hand and by Wright on the other are presumably a result of the use of different f-values, but both investigations agree in placing these temperatures well below the effective temperature (an integrated brightness-temperature) of the Sun. This is also well confirmed by measures of the equivalent widths of solar molecular lines.† The disturbing feature of this discrepancy lies in the fact that atoms are lifted to their lower states by the absorption of continuous radiation, and to some extent by collisions of the first kind, so that excitation-temperatures should be nearly the same as brightness-temperatures and kinetic temperatures. The failure to obtain even approximate equality is one of the two major puzzles presented by the curve of growth.

3.4. *The Half Half-Width.*—Our Medallist's discovery from the curve of growth that the half half-width of the solar lines is some nine times greater than their radiation-damping width has been fully confirmed, as we have seen, from more recent investigations. In a subsequent paper ‡ he has determined equivalent widths of members of the *Mg* series, $2^1\mathrm{P}-n^1\mathrm{D}$, in the solar spectrum, and has found that these strong lines, which lie on the damping part of the curve of the growth, show an increase of equivalent width with series number n. From equations 3.2 (7) and (3) we see that

$$W \propto \lambda^{\frac{3}{2}}\sqrt{f\times\delta}$$

neglecting the variation of μ with frequency, and since f decreases as $1/n^3$, it follows that the half half-width, δ, must be increasing very rapidly with series number. The greater the series number the greater the impact-diameter of the atom, and there can be little question that both in this phenomenon and in the swollen half half-widths revealed by the curve of growth we have to do with impact-widening adding itself, in accordance with equation 1.5 (18), to the natural line width.

Strömgren § has recently given a highly satisfactory, quantitative explanation of the large impact-widening shown by solar lines. Following Wildt ‖, Strömgren attributes the continuous absorption coefficient, k_0, to the photo-ionization of negative hydrogen ions. Since from equation 2.3 (10) and more clearly from 2.3 (11) the intensity ratio, r_ν, in a line depends upon the ratio $\eta=k_\nu/k_0$, it follows that lines due to different elements will give the relative abundance of negative hydrogen, and hence from Saha's ionization formula the relative abundance of atomic hydrogen. Hydrogen thus turns out to be nearly 10,000 times as abundant as all the metals combined, even greater than the

* R. B. and A. S. King, *Ap. J.*, **87**, 24, 1938.
† M. G. Adam, *M.N.*, **98**, 544, 1938.
‡ M. Minnaert and J. Genard, *Z. Astrophys.*, **10**, 377, 1935.
§ B. Strömgren, *Festschrift für E. Strömgren*, p. 218, 1940.
‖ R. Wildt, *Ap. J.*, **89**, 295, 1939 ; **90**, 611, 1939.

surprisingly high abundance predicted by Russell * in 1933. Strömgren now calculates from equation 1.4 (16) the optical impact diameter for *Na* atoms absorbing the D lines in an atmosphere of hydrogen, and finds a value of $\sigma = 4{\cdot}6 \times 10^{-8}$ cm. From the abundance of hydrogen and this value of σ, he is thus enabled by equation 1.4 (17) to calculate the collisional half half-width, δ_c. Allowing for the variation with depth in the number of negative hydrogen ions and hydrogen atoms which would be expected in an atmosphere in radiative and local thermodynamic equilibrium, he integrates the equation of transfer in accordance with the method developed by himself and mentioned in Section 2.3. From this integration, from the approximate quantum-mechanical calculation of the natural line half half-width, and from his own calculation of the collisional half half-width he is thus able to predict the profile of the D lines, and their equivalent widths. Good agreement with observation is obtained, and we may therefore regard it as established that the large half half-width of the solar lines is due to collisions with the abundant hydrogen atoms. A further confirmation of this result has been obtained by ten Bruggencate and Houtgast † from their determination of the impact-widths of two *Fe*-multiplets observed across the disc of the Sun.

3.5. *Stellar Atmospheres.*—In spite of their generally inadequate resolving power and dispersion, stellar spectroscopes can in principle give accurate equivalent widths. It is therefore possible, in the same manner as for the Sun, to construct empirical curves of growth, and to find quantitative values of excitation temperature, half half-width and of the parameter v—thus opening up an almost inexhaustible field for the quantitative study of stellar atmospheres. A striking example of such an investigation is that of Unsöld ‡ on the Bo star, τ Scorpii. From the plates obtained by Struve and himself with the Coudé and Cassegrain spectroscopes of the McDonald Observatory, Unsöld determines the equivalent widths of some 200 lines due to *H*, *He* I and II, *C* II and III, *N* II and III, *O* II and III, *Ne* II, *Mg* II, *Al* III, and *Si* III and IV. He uses theoretical oscillator strengths from multiplets and transition arrays, provisionally converted to absolute values from one or two lines which arise from transitions between hydrogen-like terms, and thus determines an empirical curve of growth for each stage of ionization of each element. His theoretical curve of growth is based on his own theory, but his results would have been essentially unchanged if Menzel's theory, as described in Section 3.2, had been used. From a comparison of the empirical and theoretical curves of growth he derives relative numbers of atoms of the various elements in the rth stage of ionization and the sth level of excitation. Owing to the high level of excitation of the lines occurring in this stellar spectrum, the number of atoms in the $(r-1)$th stage of ionization, found from an application of Boltzmann's and Saha's relations, is relatively insensitive to the assumed temperature. Assuming a temperature of 25,200 deg. K., he is thus able to derive provisional values for the number of atoms in the $(r+1)$th and the $(r+2)$th stages of ionization, provided lines from the two preceding stages are visible in the spectrum, and from these numbers by a further application of Saha's equation a provisional value for the electron-pressure and density. From the theory of Pannekoek, confirmed by the observations of Mohler and re-discussed by Inglis and Teller §, the last observable line of the Balmer series is determined by the Stark-broadening of the lines, that is by the density of the ions which in a B-type star is also

* H. N. Russell, *Ap. J.*, **78**, 239, 1933.
† P. ten Bruggencate and J. Houtgast, Z. *Astrophys.*, **20**, 149, 1940.
‡ A. Unsöld, Z. *Astrophys.*, **21**, 1, 22, 1941.
§ D. R. Inglis and E. Teller, *Ap. J.*, **90**, 439, 1939.

approximately the density of the electrons. This directly observed electron-density is greater than that found from the numbers of atoms in different stages of ionization, and hence the assumed temperature must be too low. By trial and error Unsöld thus finds the correct temperature to be 28,150 deg. K. With this temperature revised values for the relative numbers of atoms in different stages of ionization are obtained, and so finally the relative abundance (in atoms)

$$H : He : \text{Rest of elements} = 85 : 15 : 0{\cdot}24.$$

In particular $\log (H : Mg) = 4{\cdot}24$, in good agreement with Strömgren's value of 4·4 in the solar atmosphere. In a fourth paper * Unsöld confirms his $H : He$ ratio from the theory of Stark-broadening and the observed equivalent widths of the stronger lines of these two elements. Finally in a third paper † he discusses the ratio $k_0/\bar{k}$, of the continuous absorption coefficient at a given frequency to the Rosseland mean coefficient, comparing the observed value derived from the central intensities of the strong lines on the assumption that they are formed by pure absorption ($\epsilon = 1$), with the value predicted from the theory of the continuous absorption coefficient and the relative abundance of the elements.

An early and remarkable discovery by Struve and Elvey ‡ still dominates the literature of stellar curves of growth. Empirical curves of growth were found by them for the five stars—α Canis Majoris (A 2), α Lyrae (Ao), α Cygni (cA2), α Persei (F 5), and ϵ Aurigae (F5p). In addition they considered the curve of growth for 17 Leporis (Ao) determined by Hynek.§ For the first three stars a comparison of the empirical with the theoretical curve of growth yielded not unexpected values for the half half-width and the parameter v, but the remaining three stars showed a greatly extended Doppler-part corresponding to values of v of 7 km. sec.$^{-1}$ for α Persei, 20 km. sec.$^{-1}$ for ϵ Aurigae and 67 km. sec.$^{-1}$ for 17 Leporis, that is to kinetic temperatures respectively of 3×10^5, 2×10^6 and 3×10^7 deg. K. Such temperatures must be fictitious, and following a suggestion of McCrea ||, Struve and Elvey propose that the parameter v in these stars is given by $v^2 = \frac{2kT}{M} + v_t$, where v_t is the velocity component in the line of sight of masses of gas in turbulent motion with a Maxwellian distribution.

On the other hand, it has been suggested that the large values of v for these three stars arose from incorrect construction of the empirical curves of growth. Struve and Elvey's work was completed before the theory of the curve of growth was completely understood, and they plotted $\log W$, instead of $\log W/\lambda$, against $\log X_0$, a procedure which, if the lines covered a large range of wave-lengths, would give a fictitious extension to the Doppler-part of the curve of growth. In a private communication, however, Struve has pointed out that the great majority of their lines lay in the narrow range $\lambda\lambda$ 4300–4600, so that this criticism loses much of its force. In this connection the recent investigation of the curve of growth in α Persei by K. O. Wright ¶ is of the first importance. With a dispersion averaging 7 A. per mm. he has measured with great care the equivalent widths of over 1000 lines. Using empirical oscillator strengths taken from his earlier work on the Sun, he finds values of v of 3·7 km. sec.$^{-1}$ for neutral

* A. Unsöld, *Z. Astrophys.*, **23**, 75, 1944.
† A. Unsöld, *Z. Astrophys.*, **21**, 229, 1942.
‡ O. Struve and C. T. Elvey, *Ap. J.*, **79**, 409, 1934.
§ J. A. Hynek, *Ap. J.*, **78**, 54, 1933.
|| W. H. McCrea, *M.N.*, **89**, 718, 1929.
¶ K. O. Wright, *J.R.A.S. Canada*, **40**, 183, 1946.

and of 6·4 km. sec.$^{-1}$ for ionized lines, thus confirming the results of Struve and Elvey. There thus can be no question as to the reality of their discovery.

Its interpretation by "turbulence" is more open to question. In granulation, as observed on the Sun, we are familiar with a bodily motion of masses of gas in vertical streams, the motion being maintained by the energy of ionization of the abundant hydrogen, but the phenomenon of granulation does not lead to an increase in the equivalent widths of the spectrum lines. Each granule over the disk of the Sun contributes its own slightly displaced absorption line, and the sum of these displaced lines results in a washed-out profile of unchanged equivalent width. Only in the event of the moving masses of gas overlying each other and each making its own contribution to the observed absorption line will there be an increase of equivalent width.* Under these conditions the masses of gas will collide with each other, but these collisions will not be, as Milne † has pointed out, the elastic collisions contemplated in the kinetic theory. The collisions will be collisions between the individual atoms of the gas-masses, not of the gas-masses as units, and the result will be a dissipation of kinetic energy into energy of thermal agitation of the atoms. "Turbulence" therefore affords no escape from kinetic temperatures of the order of millions of degrees.

3.6. *Emission-Line Stars.*—Menzel ‡ has proposed an alternative interpretation of Struve and Elvey's curves of growth. It has long been known that many stellar lines are on the point of appearing in emission—a striking example being the *He* II line, λ 4686 which should be the strongest *He* II line in the absorption-line O-type stars, but is normally either weak, absent or appears in emission. Other examples are provided by the Balmer lines in Be stars where the early lines of the series appear in emission and the later in absorption. What is true of these stars may well be true in a less marked degree of any star. If now, as is normally assumed, the emission-line is formed above the much stronger absorption line, then as a first approximation we can regard the observed equivalent width as the algebraic sum of the absorption and emission component (assumed transparent), each with its own appropriate curves of growth. Menzel has constructed composite curves of growth in this way, and has found that the Doppler-parts of the curves, just as in Struve and Elvey's curves, are much extended. This is a most suggestive result, and provided emission-lines were formed above the absorption-lines it could provisionally be accepted as an adequate interpretation, pending a more exact treatment by integration of an appropriate equation of transfer through the stellar atmosphere. Unfortunately the evidence for the high-level production of emission is not conclusive. Consider for example the Wolf-Rayet stars—generally regarded as presenting the strongest evidence for emission-lines occurring in an extended envelope about the star.

To C. S. Beals § we owe our modern knowledge of the spectra of these stars. He is also the author of the currently accepted theory of their line-emission. These spectra are characterized by emission-lines of atomic origin with widths in some stars of 60 to 100 A. and with intensities some 10 to 20 times that of the adjacent continuous spectrum. The lines are due to *He* II (from the decrement in the Pickering series the Balmer lines of *H* are weak or absent), to *C* II, III, IV, *N* III, IV, V, *O* III, IV, V, VI and

* A. Unsöld, *Physik der Sternatmosphären*, p. 272, 1938; H. Zanstra, private communication.

† S. Chandrasekhar, *M.N.*, **94**, footnote on p. 16, 1933.

‡ D. H. Menzel, *Pop. Astr.*, **47**, 6, 66, 124, 1939.

§ C. S. Beals, *Publ. Dom. Astrophys. Obs., Victoria*, **4**, 271, 1930; **6**, 95, 1934; *J.R.A.S. Canada*, **34**, 169, 1940.

Si II, III, IV. The identification of the lines in the higher stages of ionization of carbon, nitrogen and oxygen is due to Edlén.* The stars may be classified in two parallel temperature-sequences, in one of which carbon is present to the exclusion of nitrogen (type WC), and in the other of which nitrogen excludes carbon (type WN). From careful spectrophotometry Beals has found that the profiles of these lines in some stars show a flat top, and has shown that these profiles can be interpreted as the sum of emission-lines each displaced by Doppler effect due to the uniform radial outward motion of the atoms. From the symmetry of the lines and the absence of occultation-effect†, it follows on this hypothesis that the star proper, which provides the continuous spectrum, must be small in comparison with the atmosphere of radially ejected atoms which provide the emission-lines. The atoms are thus bathed in a dilute radiation-field ‡, and cyclic transitions will tend to produce emission-lines. In the limit, such as strictly occurs only in the gaseous nebulae, we get pure ionization and recombination, and may apply Zanstra's § theory to find the ultra-violet brightness-temperature of the star. Beals finds the resulting temperatures to lie between 100,000 deg. K. for WN 5 and WC 6 and 60,000 deg. K. for WN 8 and WC 8.

Though the application of Zanstra's theory to the atmospheres of Wolf-Rayet stars is open to question, the picture of the process of emission is at least self-consistent. Beals, however, finds that the width of the emission-lines increases with decreasing ionization-potential of the carrier, and to account for this is forced to assume (i) that in their radial motion outwards the atoms are accelerated, and (ii) that progressive absorption of the ultra-violet continuous radiation from the star produces a stratification of emission similar to that shown by the planetary nebulae. From Chandrasekhar's investigation (previously cited) the first of these hypotheses leads, on any physically probable law of emission as a function of distance from the star, to rounded or peaked line-profiles, instead of the flat-topped ones so characteristically observed. The second hypothesis implies that the emission-line envelope has a great optical depth for the continuous ultra-violet radiation from the star, and it becomes difficult to see how enough of this ultra-violet radiation can escape from the envelope for the Wolf-Rayet star to act as the nucleus and exciting source for a planetary nebula—as in fact happens in such typical planetary nebulae of high surface-brightness as NGC I 418, NGC 6543, NGC 6572 and NGC II 5217. These difficulties are not necessarily insuperable, but they do render Beals's picture of the emission in Wolf-Rayet less attractive.

A detailed study has recently been made of the star HD 193576 (=V 444 Cygni). This star was discovered by O. C. Wilson || to be a spectroscopic binary, consisting of a Wolf-Rayet component (WN 5·5) and an absorption-line O-type component (O6) ¶ moving in circular orbits in a period of 4·21 days. The mean velocity of the Wolf-Rayet component, according to Wilson, is 56 km. sec.$^{-1}$, and of the O-type component is −34 km. sec.$^{-1}$, the latter being about the velocity of the system as judged from the radial velocities of early-type stars in the same vicinity of the sky. He therefore concluded that the lines of the Wolf-Rayet component had a red-shift of 90 km. sec.$^{-1}$, and he offered some evidence ** that the Wolf-Rayet stars as a class showed a similar

* B. Edlén, *Z. Astrophys.*, **7**, 378, 1933.
† S. Chandrasekhar, *M.N.*, **94**, 522, 1934.
‡ S. Rosseland, *Ap. J.*, **63**, 218, 1926.
§ H. Zanstra, *Ap. J.*, **65**, 50, 1927; *Publ. Dom. Astrophys. Obs., Victoria*, **4**, 209, 1931.
|| O. C. Wilson, *Ap. J.*, **91**, 379, 1940.
¶ C. S. Beals, *M.N.*, **104**, 205, 1944.
** O. C. Wilson, *Ap. J.*, **91**, 394, 1940.

red-shift. He discards after examination the hypothesis that this red-shift is a result of absorption-lines lying to the violet of the emission lines, and concludes that it is due to an Einstein gravitational displacement. If this be true, other not inapplicable data for HD 193576 suggest that the emission-lines are formed at the surface of a star with a radius rather smaller than that of Jupiter. Subsequently Gaposchkin * has found that HD 193576 is an eclipsing variable, and has published a provisional photometric orbit. An accurate light-curve by Kron and Gordon † has, however, revealed a surprising feature for an eclipsing variable with a circular orbit, namely that the primary minimum, when the O-type star passes behind the Wolf-Rayet star, is nearly twice as wide as the secondary minimum. This feature of the light-curve has been discussed by Kopal, Russell and Mrs Shapley ‡, and these writers conclude that the Wolf-Rayet star must be surrounded by an extensive, semi-transparent envelope which itself emits no light, but which is sufficiently opaque to absorb some of the light from the O-type star as it passes behind. Since Kron's potassium hydride photoelectric cell is sensitive in a half width 4100 to 4800 A., containing according to Beals (*loc. cit.*) much the strongest emission-line, *He* II, λ 4686, in the Wolf-Rayet spectrum, it does not seem probable that the emission-lines can originate in this non-luminous envelope. A re-interpretation of the photometric orbit in the light of Beals's careful photometric study of variations in the spectrum may reverse this verdict, but at present at least the star HD 193576 does not give strong support § for the hypothesis that the emission-lines of Wolf-Rayet stars are necessarily formed high-up in the atmosphere.

On the other hand emission-line stars, notably the Me stars, are known where it is reasonably certain that the emission-lines are formed below the absorption-lines. The hydrogen emission-lines in these stars ‖ have a peculiar decrement with $H\delta$ as the strongest line closely followed by $H\gamma$ and $H\zeta$. The other hydrogen emission-lines, which are much weaker, occur where there are strong absorption lines due to *Ca* II (H line), *Fe* I, *V* I and heavy absorption-bands of *TiO*, all presumably overlying the emission-lines.

Returning now to Menzel's interpretation of the extended Doppler-part of Struve and Elvey's curves of growth, the reproduction of this anomaly by composite curves of growth cannot be regarded as entirely convincing. When the evidence for the high-level formation of emission-lines in Wolf-Rayet stars is suspect, and when the Me stars have their absorption-lines formed above the emission-lines, it is no longer legitimate to assume, even as a first approximation, that the equivalent width of a composite line will be given by the algebraic addition of its absorption- and emission-components. Thus, though Menzel's interpretation is physically more satisfactory than that of "turbulence", it can only be established by integration of an equation of transfer containing the part, j'_ν of the line-emission coefficient which Eddington omitted (Section 2.3). Until this has been done and the extended Doppler-part of the curve of growth obtained, Struve and Elvey's "turbulence" must be added to the low excitation-temperature of the Sun as the second major puzzle presented by the curve of growth.

* S. Gaposchkin, *Ap. J.*, **93**, 202, 1941.

† G. E. Kron and K. C. Gordon, *Ap. J.*, **97**, 311, 1943.

‡ Z. Kopal, *Ap. J.*, **100**, 204, 1944; H. N. Russell, *Ap. J.*, **100**, 213, 1944; Z. Kopal and M. B. Shapley, *Ap. J.*, **104**, 160, 1946.

§ O. C. Wilson, *Ap. J.*, **95**, 402, 1942.

‖ P. W. Merrill, *Spectra of Long-Period Variable Stars*, pp. 45, 71, 1940.

4. *Future Work in Astronomical Spectroscopy*

4.1. *The Future.*—In the curve of growth we have considered one application of astronomical spectroscopy to the problems of astrophysics. Another application, even more promising, is to the profiles of solar absorption-lines obtained by high-resolution spectroscopy, but here I can only refer to the invaluable pioneer work in this field by Shane, Redman and Houtgast.* Enough has been said, however, at least to indicate the great power of this new technique in astrophysics, and it only remains to consider where improvements can be made in its future application. On three points at least immediate research is required. These are the observational determination of equivalent widths, the values of atomic constants and the modification of the equation of transfer. Let us consider each of these.

4.2. *Determination of Equivalent Widths.*—Two requirements must be satisfied if an accurate equivalent width is to be obtained. In the first place the profile of the observed line, the resultant of the true profile and the slit-pattern of the spectroscope, must be determined by accurate photographic spectrophotometry, especial care being taken to avoid systematic errors arising both from faulty calibration and from Eberhard-effect. The spectrophotometry (and indeed the wave-length measurement) must meet the same high standards which are satisfied in the determination of true profiles by high-resolution spectroscopy. The accuracy, as might have been anticipated, increases with increase of dispersion, and it is no doubt due to this, as well as to the accurate spectrophotometry, that the equivalent widths of solar lines found by Allen and by K. O. Wright (from measures in the *Utrecht Atlas*) are in such relatively good agreement.

In the second place particular care must be taken in fitting the wings of the observed profile into the continuous background. Provided the resolving power of the spectroscope is sufficiently great, our Medallist's † method should always be followed. From equations 3.2 (2) and 1.5 (19), expressed in wave-lengths, it follows that in the *wings* of a line-profile

$$r_\lambda = \frac{1}{1 + C/(\Delta\lambda)^2},$$

where C is a constant. In general the blackening of the plate due to the continuous background varies across the width of the line, either because of a variation in intensity or sensitivity of the plate. If this variation is linear, and in a small wave-length region it can generally be so regarded, we may write the intensity-ratio in the line in the form

$$r_\lambda = \frac{I_\lambda}{I_0 + m \times \Delta\lambda},$$

where m is a constant to be found from measures of the continuous background on either side of the line and well separated from it. From these two equations we thus find

$$I_\lambda - m \times \Delta\lambda = I_0 - C\frac{I_\lambda}{(\Delta\lambda)^2}. \qquad (1)$$

Consequently if we plot $I_\lambda - m \times \Delta\lambda$ against $I_\lambda/(\Delta\lambda)^2$, we shall get a straight line whose slope is C and whose intercept on the axis of ordinates is the required value of I_0, the intensity of the true continuous spectrum at the centre of the line. The error in equivalent width which results from a small error in the intensity of the continuous

* C. D. Shane, *L. O. Bull.*, **16**, 76, 1932 ; **19**, 119, 1941; R. O. Redman, *M.N.*, **95**, 742, 1935; **98**, 325, 1938 (a review); J. Houtgast, Dissertation, Utrecht, 1942.

† M. Minnaert, *Z. Astrophys.*, **10**, 40, 1935.

background, such as may result from the usual method of drawing in the background by eye, may be approximately evaluated by this same method, and Minnaert finds that when the background is put in at $0{\cdot}96I_0$, the measured equivalent width is some 23 per cent too small—a disastrously large error. On the other hand this method is not applicable when the line is so faint that the observed profile is wholly determined by the slit-pattern of the spectroscope. In this event, however, the faint lines are of a standard shape, and a constant times the equivalent width can be determined by the measurement of the central intensity ; the constant can be evaluated by finding the equivalent widths of a number of faint lines by the ordinary method.

As long as high dispersion and reasonable resolving power can be used, as in solar spectra, these two requirements can be met and should suffice to give accurate equivalent widths. In the spectra of stars, particularly the interesting faint ones, high dispersion cannot be employed, and precautions must be doubled to be sure the two requirements are satisfied. Particularly insidious are errors due to Eberhard-effect and to instrumental blending of lines, and it is not surprising that in the early days of astronomical spectroscopy the equivalent widths of the same line given by different observers were occasionally in the ratio of two or three to one. The previously mentioned paper of K. O. Wright on α Persei is a good example of the care taken in the best modern work ; particularly noteworthy is his use of a reasonable dispersion, averaging 7 A. per mm., and his neat method of overcoming plate-grain fluctuation for the faint lines which fix the vital Doppler-part of the curve of growth. That there is a systematic difference of 25 per cent between his equivalent widths and those determined slightly earlier by Miss Steel * for the same star is only evidence of how difficult the problem is. This very difficulty makes it desirable that some standard star should be chosen, and the equivalent widths of its lines determined with the highest possible accuracy by a number of observers : in view of Wright's work and Dunham's † line identifications, α Persei would be very suitable. Intercomparison of the equivalent widths determined by different observers should reveal the major sources of systematic error, and thus lead to substantial improvements in the technique employed for stellar spectra. Further the finally adopted definitive values of the equivalent widths would then be available as standards for future investigations, so that an observer wishing to try out some new method, or to employ a small-dispersion spectroscope for faint stars, would have a control on his technique.

4.3. *Laboratory Determination of Atomic Constants.*—The quantum-mechanical calculation of atomic constants is both difficult and, for elements other than hydrogen, approximate. Theoretical physicists can, therefore, scarcely be expected to initiate such investigations until accurate laboratory values are available as a stimulus and a guide. Without accurate atomic constants for the astrophysically important lines, astronomical spectroscopy is impossible, and the responsibility for their determination in the laboratory lies squarely with the astronomer. The constants with which we are concerned are the oscillator-strength, f, and the half half-widths, δ, due to radiation-damping, and δ_c, due to impact-broadening.

A valuable start on the determination of relative and absolute f-values has already been made at Mt. Wilson by R. B. King.‡ Using the vacuum-tube furnace of A. S. King,

* H. R. Steel, *Ap. J.*, **102**, 43, 1945.

† T. Dunham, jr., *Contributions Princeton Univ. Obs.*, No. 9, 1929.

‡ R. B. and A. S. King, *Ap. J.*, **82**, 377, 1935 ; **87**, 24, 1938 ; R. B. King and D. C. Stockbarger, *Ap. J.*, **91**, 488, 1940 ; R. B. King, *Ap. J.*, **94**, 27, 1941 ; **95**, 78, 1942.

backed by a source of continuous spectrum, and a concave-grating spectroscope with a dispersion of 1·86 A. per mm., R. B. King and his collaborators have measured the equivalent widths of faint lines of different elements. These lines lie on the Doppler-part of the curve of growth, so that for exponential absorption (equation 2.2 (5)) in the laboratory, equation 3.2 (5) is applicable if we substitute the length, H, of the absorption tube for our quantity μ. We thus get

$$\frac{W}{\lambda} = \frac{\pi\epsilon^2}{mc} N_i H f \frac{\lambda}{c},$$

where N_i is the number of atoms, in the lower of the two states concerned, per unit volume. If now we assume thermodynamical equilibrium in the furnace we have from Boltzmann's law

$$N_i = N_1 \frac{q_i}{q_1} e^{-E_i/kT},$$

where E_i is the excitation potential of the level i. Hence for this particular line *

$$f = \left[\frac{mc^2}{\pi\epsilon^2} \frac{q_1}{q_i} e^{E_i/kT}\right] \frac{W}{\lambda^2} \frac{1}{N_1 H}, \tag{2}$$

where the quantity in square brackets contains constants known from the term-structure of the spectrum, and where the quantities W/λ^2 and $N_1 H$ have to be determined respectively from spectrophotometry and from the vapour-pressure of the element at the temperature of the furnace.

These exceedingly valuable investigations which, it is to be hoped, R. B. King will be able to extend to elements in addition to *Fe* and *Ti*, require independent confirmation. In particular it would be useful to employ Roschdestwensky's † exceedingly accurate "hook-method" to the determination of refractive index, as well as magneto-rotation methods. All three methods suffer unfortunately from the limitation that they determine $N_i f$, and absolute values of f can only be found from a vapour-pressure determination—a great source of inaccuracy since a vapour-pressure determination does not distinguish between the population of atoms, in which we are interested, and the population of temporary molecules, which may be formed in evaporation.

A method of determining the oscillator-strength, which is independent of N, is based on equation 1.2 (9). Since from its definition the Einstein transition coefficient, A_{ji}, is the reciprocal of the average time, τ, which the atom spends in state j before emitting the line of frequency ν_{ij}, we have

$$f = \tfrac{1}{3} \frac{q_j}{q_i} A_{ji} = \tfrac{1}{3} \frac{q_j}{q_i} \frac{1}{\tau}. \tag{3}$$

Wien's determination ‡ of average life-times, and therefore of oscillator-strengths, from the decay of radiation along a column of positive rays is well known, but is not likely to yield accurate results because of subsequent cascade-jumps down to the upper level concerned from captures of electrons on still higher levels. An atomic beam illuminated by a narrow pencil of exciting radiation of the required frequency, as in Koenig and Ellett's § experiment, should be exceedingly accurate, but unfortunately the method is limited to long life-times, that is small values of f, by the low speed of the atoms in

* D. H. Menzel and L. Goldberg, *Ap. J.*, **85**, 40, 1937.
† D. Roschdestwensky, *Ann. Phys.*, **39**, 307, 1912 ; *Trans. Opt. Inst. Leningrad*, **2**, No. 13, 1921.
‡ W. Wien, *Ann. Phys.*, **73**, 483, 1924.
§ H. D. Koenig and A. Ellett, *Phys. Rev.*, **39**, 576, 1932.

the atomic beam. The method might be extended to shorter life-times by the use of high optical magnification using a Burch reflecting microscope * with its long working distance. A more speculative possibility is the illumination of a stationary mass of gas by an exciting beam modulated by a Kerr-cell, and a determination of the decay-time of the thus excited radiation by two spectroscopes at different distances from the gas with their exposures regulated by two synchronous Kerr-cells. The trapping of the excited radiation† would have to be allowed for, while for lines other than resonance lines Wood's‡ method of controlled optical excitation would have to be used. An admirable discussion of a wide variety of methods of determining life-times will be found in Mitchell and Zemansky §, and with this critical record of past successes and failures it should be possible to find a satisfactory method of direct determination of oscillator-strengths.

The direct determination of the natural half half-width, δ, in the absence of collisions is, thanks to the classical investigation of Minkowski, already cited, comparatively simple. To avoid broadening due to the collisions of atoms with themselves, for which the optical impact-diameter is very large, it is necessary to use exceedingly low vapour-pressures and therefore a very long absorbing tube. The considerable technical difficulties thus imposed could be minimized by the method of controlled multiple reflections || in a short tube. Similarly the use of spectroscopes of very high resolving power could be avoided by measuring equivalent width and finding the radiation-damping part of the curve of growth by step-by-step increases in the equivalent length of the tube.

The determination of the collisional half half-width, δ_c, for an atom in an atmosphere of foreign atoms is also well within the range of the astronomical spectroscopist by a repetition of Minkowski's work. The difficulty here is that the interesting atmosphere is one of hydrogen atoms, and since the dissociation potential of the hydrogen molecule is 4·45 electron volts such an atmosphere is very difficult to obtain in the laboratory. Wood ¶ has been able to pump hydrogen atoms out of the centre of his long discharge-tube, but their life-time is short and the method does not appear promising. Failing this or some similar method it will be necessary to find collisional half half-widths for the atom in an atmosphere of the various inert gases, and then, following Strömgren in his already quoted paper on collisional broadening in the Sun, semi-empirically to extrapolate to a hydrogen atmosphere.

4.4. *The Equation of Transfer.*—Eddington's equation of transfer, which has been the basis of all work in astronomical spectroscopy, suffers, as he clearly stated, from two limitations. It assumes first that the radiation is coherently scattered, and secondly that arrivals in the excited state by collisions of the first kind, by captures and by cascade-jumps down from higher states may be neglected. Since except under restrictive conditions, not fulfilled in stellar atmospheres, the re-emitted radiation is of different frequency from the absorbed, and since in stellar atmospheres giving emission or incipient emission-lines there must be arrivals in the excited state in addition to those resulting from the absorption of quanta by the atom in its lower state, it is clear that future progress in astronomical spectroscopy will depend upon the removal of these limitations.

* C. R. Burch, *Proc. Phys. Soc.*, **59**, 41, 1947.
† E. A. Milne, *J. Lond. Math. Soc.*, **1**, 40, 1926.
‡ R. W. Wood, *Physical Optics*, 3rd ed., p. 599, 1934.
§ A. G. G. Mitchell and M. W. Zemansky, *Resonance Radiation and Excited Atoms*, 1934.
|| H. R. Kratz and J. E. Mack, *J.O.S.A.*, **32**, 457, 1942.
¶ R. W. Wood, *Proc. Roy. Soc.*, A, **102**, 1, 1922.

A Fabian approach is probably the best in so difficult a problem, but it is of some interest at least to try a frontal attack. Consider for example the general and exact equation of transfer (equation 2.1 (1)) for an atmosphere stratified in plane parallel layers

$$\cos\theta \frac{dI_\nu(x,\theta)}{dx} = (k_0 + k_\nu)I_\nu(x,\theta) - \{j_0(x) + j_\nu(x)\}, \tag{4}$$

and let us evaluate the absorption and emission coefficients k_ν and j_ν. Designate the ground state of the atom by 1, the next higher state making transitions with the ground state by 2, while 3 is a still higher state from which transitions to 2 are possible. Consider transitions between states 2 and 3. Neglecting for simplicity the stimulated emissions, the microscopic transition coefficients are from equation 1.2 (12) given by

$$a_{32} = A_{32}\frac{\delta_2}{\pi}\frac{dE_2/h}{\delta_2^2 + \left(\frac{E_2 - E_2^0}{h}\right)^2},$$

$$b_{23} = B_{23}\frac{\delta_3}{\pi}\frac{dE_3/h}{\delta_3^2 + \left(\frac{E_3 - E_3^0}{h}\right)^2}.$$

Introducing Spitzer's* notation, the distance from the centre of an energy level in frequency units is

$$s_2 = \frac{E_2 - E_2^0}{h}\ ;\quad s_3 = \frac{E_3 - E_3^0}{h}\ ;\quad s_3 - s_2 = \frac{E_3 - E_2}{h} - \frac{E_3^0 - E_2^0}{h} = \nu_{23} - \nu_{23}^0 = \Delta\nu,$$

so that the microscopic transition coefficient becomes

$$a_{32} = A_{32}\frac{\delta_2}{\pi}\frac{ds_2}{\delta_2^2 + s_2^2}\ ;\quad b_{23} = B_{23}\frac{\delta_3}{\pi}\frac{ds_3}{\delta_3^2 + s_3^2}. \tag{5}$$

Now let the number of atoms in state i between s_i and $s_i + ds_i$ be

$$N_i W^*(s_i)ds_i, \text{ where } \int_{-\infty}^{\infty} W^*(s_i)ds_i = 1,$$

and where the asterisk is used to denote that $W^*(s_i)ds_i$ is the actual distribution of atoms in the level i, as opposed to the distribution resulting from natural excitation or thermodynamical equilibrium. Hence for atoms at rest the absorption-coefficient will be given by

$$k_\nu = k(\nu_{23}^0 + \Delta\nu) = \frac{h\nu}{c}N_2 B_{23}\frac{\delta_3}{\pi}\int_{-\infty}^{\infty}\frac{W^*(s_2)ds_2}{\delta_3^2 + s_3^2} = \frac{h\nu}{c}N_2 B_{23}\frac{\delta_3}{\pi}\int_{-\infty}^{\infty}\frac{W^*(s_2)ds_2}{\delta_3^2 + (s_2 + \Delta\nu)^2}, \tag{6}$$

where the integration is to be carried out with respect to s_2 and subject to the condition that $\Delta\nu$ is constant. Similarly the volume-coefficient of emission will be given by

$$j_\nu = j(\nu_{23}^0 + \Delta\nu) = \frac{h\nu}{4\pi}N_3 A_{32}\frac{\delta_2}{\pi}\int_{-\infty}^{\infty}\frac{W^*(s_3)ds_3}{\delta_2^2 + (s_3 - \Delta\nu)^2}, \tag{7}$$

where the integration is to be carried out with respect to s_3, subject to the condition that $\Delta\nu$ is constant.

If the atoms have a Maxwellian distribution of velocity, the contribution to the absorption coefficient of those atoms with a velocity between u and $u + du$ will be

$$k(\nu_{23}^0 + \Delta\nu)du = \frac{h\nu}{c}N_2 B_{23}\left(\frac{M}{2\pi kT}\right)^{\frac{1}{2}}\frac{\delta_3}{\pi}e^{-Mu^2/2kT}du\int_{-\infty}^{\infty}\frac{W^*(s_2)ds_2}{\delta_3^2 + \left(s_2 + \Delta\nu + \frac{u}{c}\nu_{23}^0\right)^2},$$

* L. Spitzer, *M.N.*, **96**, 794, 1936.

and the total absorption coefficient will be

$$k(\nu_{23}^0+\Delta\nu)=\frac{h\nu}{c}N_2B_{23}\left(\frac{M}{2\pi kT}\right)^{\frac{1}{2}}\frac{\delta_3}{\pi}\int_{-\infty}^{\infty}e^{-Mu^2/2kT}\,du\int_{-\infty}^{\infty}\frac{W^*(s_2)ds_2}{\delta_3^2+\left(s_2+\Delta\nu+\frac{u}{c}\nu_{23}^0\right)^2}.$$

Now substitute

$y=\left(\frac{M}{2kT}\right)^{\frac{1}{2}}u$, so that $\frac{u}{c}\nu_{23}^0=by$ where $b=\left(\frac{2kT}{M}\right)^{\frac{1}{2}}\frac{\nu_{23}^0}{c}$; also put $\omega=\frac{\Delta\nu}{b}$, and $a_3=\delta_3/b$,

and we finally get

$$k(\nu_{23}^0+\Delta\nu)=\frac{h\nu}{c}N_2B_{23}\frac{1}{b\sqrt{\pi}}\frac{a_3}{\pi}\int_{-\infty}^{\infty}e^{-y^2}dy\int_{-\infty}^{\infty}\frac{W^*(s_2)ds_2}{a_3^2+\left(\frac{s_2}{b}+\omega+y\right)^2}. \tag{8}$$

Similarly for atoms in motion the emission-coefficient becomes

$$j(\nu_{23}^0+\Delta\nu)=\frac{h\nu}{4\pi}N_3A_{32}\frac{1}{b\sqrt{\pi}}\frac{a_2}{\pi}\int_{-\infty}^{\infty}e^{-y^2}dy\int_{-\infty}^{\infty}\frac{W^*(s_3)ds_3}{a_2^2+\left(\frac{s_3}{b}-\omega-y\right)^2}. \tag{9}$$

Equations (8) and (9), as may be readily seen, reduce to equations (6) and (7) for values of $\Delta\nu\gg b$, that is if we work well out in the line wings. In what follows we shall use the absorption and emission coefficients given by (6) and (7), thus implying this restriction on the value of $\Delta\nu$.

4.41. *Application to Resonance Line in Solar Atmosphere.*—Now let us apply the exact equation of transfer (4) and the absorption- and emission-coefficients derived above to a resonance line, resulting from a transition between states 1 and 2. Level 1 with its long life and its small impact-radius will be *assumed* to be infinitely narrow. Equations (6) and (7) thus become

$$k(\nu_{12}^0+\Delta\nu)=\frac{h\nu}{c}N_1B_{12}\frac{\delta_2}{\pi}\frac{1}{\delta_2^2+s_2^2}, \tag{10}$$

$$j(\nu_{12}^0+\Delta\nu)=\frac{h\nu}{4\pi}N_2A_{21}W^*(s_2). \tag{11}$$

Our *second assumption* will be that

$$W^*(s_2)=\frac{\delta_2^*}{\pi}\frac{1}{\delta_2^{*2}+s_2^2}. \tag{12}$$

This is equivalent to assuming that all methods whereby the atoms get into state 2 finally result in a normal distribution among sub-levels characterized by the half half-width $\delta_2^*=\delta_2+\delta_c$, the sum of the natural and the collisional half half-widths. On this assumption equation (11) becomes

$$j(\nu_{12}^0+\Delta\nu)=\frac{h\nu}{4\pi}N_2A_{21}\frac{\delta_2^*}{\pi}\frac{1}{\delta_2^{*2}+(\Delta\nu)^2}, \tag{13}$$

where

$$s_2=\frac{E_2-E_2^0}{h}=\nu_{12}-\nu_{12}^0=\Delta\nu.$$

Hence for two frequencies $\Delta\nu_1$ and $\Delta\nu_2$, each much larger than δ_2^* we have

$$\frac{j(\nu_{12}^0+\Delta\nu_1)}{j(\nu_{12}^0+\Delta\nu_2)}=\frac{\delta_2^{*2}+(\Delta\nu_2)^2}{\delta_2^{*2}+(\Delta\nu_1)^2}=\left(\frac{\Delta\nu_2}{\Delta\nu_1}\right)^2. \tag{14}$$

Similarly

$$\frac{k(\nu_{12}^0+\Delta\nu_1)}{k(\nu_{12}^0+\Delta\nu_2)}=\frac{\delta_2^2+(\Delta\nu_2)^2}{\delta_2^2+(\Delta\nu_1)^2}=\left(\frac{\Delta\nu_2}{\Delta\nu_1}\right)^2. \tag{15}$$

Now returning to our differential equation (4), introduce the optical depth

$$\tau_0=\int_0^x k_0 dx$$

and the symbol

$$\eta=\frac{k(\nu_{12}^0+\Delta\nu)}{k_0}.$$

The equation of transfer now takes the form

$$\cos\theta\frac{dI_\nu(\tau_0,\theta)}{d\tau_0}=(1+\eta)I_\nu(\tau_0,\theta)-\frac{j_0+j(\nu_{12}^0+\Delta\nu)}{k_0}, \tag{16}$$

and this may be formally expressed as an integral equation

$$I_\nu(0,\theta)=\int_0^\infty\frac{j_0+j(\nu_{12}^0+\Delta\nu)}{k_0}e^{-\sec\theta\int_0^t(1+\eta)dt\sec\theta\,dt}. \tag{17}$$

This gives the surface-brightness in the line at the frequency $\nu_{12}^0+\Delta\nu$ as a function of position θ on the disk of the Sun. The surface-brightness in the adjacent continuous spectrum, where $j_\nu=k_\nu=0$, is given by

$$I_0(0,\theta)=\int_0^\infty\frac{j_0}{k_0}e^{-t\sec\theta}\sec\theta\,dt. \tag{18}$$

For some value $\Delta\nu_1$ assume now a hypothetical variation of the corresponding η_1 with optical depth τ_0, and as shown elsewhere * find by a solution of linear equations, one for each value of θ, the values of $(j_0+j_\nu)/k_0$ and j_0/k_0 which satisfy equations (17) and (18). Note that j_0/k_0 obtained as a function of optical depth, τ_0, is definitive, but that j_ν/k_0 depends upon the hypothetical variation of η_1 with τ_0.

Now repeat this process for some other frequency $\Delta\nu_2$ in the line-wing. From equation (15) the corresponding values of η_2 are given in terms of the originally assumed η_1 by

$$\eta_2=\left(\frac{\Delta\nu_1}{\Delta\nu_2}\right)^2\eta_1,$$

and if our hypothetical variation of η_1 were correct then by (14) the two values of j_ν should at each optical depth be in the ratio

$$\frac{j(\nu_{12}^0+\Delta\nu_2)}{j(\nu_{12}^0+\Delta\nu_1)}=\left(\frac{\Delta\nu_1}{\Delta\nu_2}\right)^2. \tag{14}$$

If this equation is not satisfied then we must commence the whole process again with a new hypothetical variation of η_1 with τ_0, and repeat, if necessary, again and again until (14) is true at each optical depth. Once this condition is satisfied, then by (10) and (13) we shall have found

$$\frac{j(\nu_{12}^0+\Delta\nu)}{k_0}=\frac{1}{k_0}\frac{h\nu}{4\pi}N_2A_{21}\frac{\delta_2^*}{\pi}\frac{1}{\delta_2^{*2}+(\Delta\nu)^2}, \tag{19}$$

$$\eta=\frac{1}{k_0}\frac{h\nu}{c}N_1B_{12}\frac{\delta_2}{\pi}\frac{1}{\delta_2^2+(\Delta\nu)^2} \tag{20}$$

as functions of optical depth in the atmosphere. Provided the atomic constants A_{21},

* H. H. Plaskett, *M.N.*, **101**, 3, 1941.

B_{12} and δ_2 are known, this means that we have found $N_2\delta_2^*/k_0$ and N_1/k_0 as functions of optical depth.

To make any further progress we may proceed by successive approximations. If we assume the atmosphere to be in local thermodynamic equilibrium, then

$$\frac{j_0}{k_0} = \frac{2h\nu^3}{c^2} e^{-h\nu/kT} \text{(giving the temperature, } T, \text{ as a function of } \tau_0),$$

which is the form Planck's law takes when stimulated emissions are neglected. Then from (19) and (20) $j_\nu/k_0\eta$, which is known as a function of optical depth, is given by

$$\frac{j_\nu}{k_0}\frac{1}{\eta} = \frac{j_\nu}{k_\nu} = \frac{c}{4\pi}\frac{8\pi h\nu^3}{c^3}\frac{q_1}{q_2}\frac{N_2}{N_1}\frac{\delta_2^*}{\delta_2}\frac{\delta_2^2+(\Delta\nu)^2}{\delta_2^{*2}+(\Delta\nu)^2}, \tag{21}$$

using the relation 1.2 (10) between Einstein coefficients. But in local thermodynamic equilibrium

$$\frac{N_2}{N_1} = \frac{q_2}{q_1} e^{-h\nu/kT}, \tag{22}$$

so that

$$\frac{j_\nu}{k_0} \times \frac{1}{\eta} = \frac{2h\nu^3}{c^2} e^{-h\nu/kT}\frac{\delta_2^*}{\delta_2}\frac{\delta_2^2+{}'(\Delta\nu)^2}{\delta_2^{*2}+(\Delta\nu)^2} = \frac{j_0}{k_0}\frac{\delta_2^*}{\delta_2}\frac{\delta_2^2+(\Delta\nu)^2}{\delta_2^{*2}+(\Delta\nu)^2},$$

from which we can find δ_2^* and thus, from equations (19) and (20), N_2/N_1 as functions of optical depth. If the latter agrees with (22), our assumption of local thermodynamical equilibrium is justified. Otherwise we may put the observed value of N_2/N_1 from the assumption of local thermodynamical equilibrium back in (21), and get a second approximation to it and to δ_2^*.

The method as described is sufficient to find N_i/N_1 and δ_1^* for any level i which gives an absorption-line by transitions from the ground state. For levels other than these, say a level j which makes transitions with a level i for which the population-ratio and the quantity δ_i^* are known from the foregoing procedure, explicit expressions for $k(\nu_{ij}^0+\Delta\nu)$ and $j(\nu_{ij}^0+\Delta\nu)$ can be derived from equations (6), (7) and (12) with δ_j^* and N_j as the only unknowns. These unknowns are to be derived as before from the absorption line ν_{ij}.

No originality is claimed for the foregoing discussion which is closely modelled on Spitzer's * fundamental paper on non-coherent scattering and follows a suggestion of ten Bruggencate.† If the two assumptions on which it is based are valid and if no error has been made, the discussion does, however, suggest that it may be possible, to remove the limitations of Eddington's form of the equation of transfer, at least for the solar atmosphere. The more difficult problem of a stellar atmosphere has not been examined, but it is to be hoped that this problem and the whole question of the equation of transfer will be discussed by theoretical astrophysicists.

Conclusion.—We have now hurriedly and imperfectly examined the theory, a few of the results and some of the future needs of astronomical spectroscopy. In the 20 years since Unsöld's papers astrophysics has made enormous strides. If this progress is to be maintained, however, it is essential that the applications of astronomical spectroscopy should be multiplied. Even to-day I get the impression, perhaps wrongly, that too many observational papers in astrophysics are based on eye-estimates of line-intensity

* L. Spitzer, *M.N.*, **96**, 794, 1936.
† P. ten Bruggencate, *Z. Astrophys.*, **4**, 159, 1932.

and on line-shapes from unreduced microphotometer tracings. At the best these are only exploratory methods, which can make no permanent contribution to the science of astrophysics, and which recall all too clearly Kelvin's remark—

> " I often say that when you can measure what you are speaking about and express it in numbers you know something about it ; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind: it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of *science*, whatever the matter may be ". (*Popular Lectures and Addresses*, 2nd ed., **1**, 80, 1891.)

If this be our text the applications of astronomical spectroscopy will multiply, and the future of astrophysics will be assured.

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